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COMPUTER MAPPING
as an aid in
AIR POLLUTION STUDIES

VOLUME TWO: INDIVIDUAL REPORTS

REPORT C
ST. LOUIS REGION STUDY -- PART III

by
Donald S. Shepard

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A detailed report of an individual case study of the St. Louis region is presented. The report is divided into five sections: Air pollution and electric power generation; Elements of the load shifting model; Determination of optimum solution; Operating the loan-shifting model; and conclusions. Two appendices are included in addition to the appendix of computer graphics produced.

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PREFACE

From July 1, 1968 through December 31, 1969, the Laboratory for Computer Graphics and Spatial Analysis conducted a demonstration of several conceptual, methodological, and technical approaches to problems in the field of air pollution, employing computer-produced maps and allied displays. This work was done under a grant (No. 68A-2405D) from the Division of Control Agency Development, National Air Pollution Control Administration (NAPCA), Public Health Service, U. S. Department of Health, Education, and Welfare.

The results of this study, taken in its entirety, should make an important contribution to the work of Federal, state, and local air pollution agencies, especially in their efforts to determine the best control strategies for use in air quality control regions. The computer is an ideal tool for relating and combining sets of data, and for considering alternatives. For instance, graphic displays can contribute significantly to the evaluation of both short-term and long-term control strategies.

In demonstrating "the use of computer graphics as a means for more clearly portraying data related to the sources, distribution, and community effects of air pollution," the primary emphasis was on case studies for specific areas. The secondary emphasis, to support and complement the case studies, included:

(a) "the development of instructional manuals covering the procedures required for the preparation and interpretation of computer maps of various kinds, as related to air pollution,"

(b) "the use of certain newly developed techniques for describing, analyzing, and portraying quantitative surfaces and movements relative to such surfaces, as related to air pollution," and

(c) "an appraisal of alternative equipment, techniques, and computer programs presently or potentially available for the production of computer graphic displays pertinent to air pollution."

The case study regions were selected in consultation with NAPCA. Considerations included:

(a) sufficient air quality, emission, and related socio-economic and meteorological data--spatially distributed over the region--to enhance the likelihood of adequately demonstrating the mapping techniques;

(b) representative problems in data handling and mapping so that the techniques demonstrated would have applicability to as many other areas as possible;

(c) special problems in data handling and mapping so that as many techniques as possible could be adapted, developed, and tested;

(d) areas of which NAPCA and the individual investigators had special knowledge and could therefore utilize relevant research to enhance the study;

(e) areas where an immediate interest in mapping had been expressed for on-going Federal, state, and local air pollution activities.

Other research was undertaken to support and complement the case studies, and, in particular, to provide:

(a) the widest possible distribution of the mapping programs and accompanying explanation of the techniques through

    i) copies of the Laboratory's SYMAP Computer mapping program,
    ii) an introductory correspondence course in the SYMAP program,
    iii) general program description and supplementary explanation for the existing user-manuals;

(b) a general review of present and potential hardware, output devices, and programs applicable to computer graphic displays of air pollution and related data;

(c) means for predicting, projecting, and correlating air pollution and related data, utilizing the latest knowledge in planning, geography, and spatial analysis in general;

(d) dissemination of information on approaches and techniques to Federal, state, and local air pollution agencies, especially for use in the air quality control regions.

The final report is divided into two parts: Volume One: Summary, and Volume Two: Individual Reports--the detailed reports on the case study areas and the technical reports related to other research undertaken. The pertinent graphic displays are included with the appropriate individual report and a complete set is provided with the Summary Volume.

Introductory sections describing the air pollution and related data used are provided in the major case study reports for St. Louis and Kansas City; these should be referred to by anyone unfamiliar with the types of data and problems existing in this field. Detailed discussions of special data handling and mapping techniques are presented either as appendices to case study reports, or in separate technical reports.

The Summary Volume includes a discussion of all the areas of research undertaken and contains the complete table of contents for the reports of Volume Two. This should provide a useful reference of the special problems and technical discussions of one report which may be of interest to the reader of another detailed report.

The St. Louis Project was the major case study Region examined under the demonstration grant. Consequently, the results are presented in three separate reports: Part I deals with the general mapping techniques; Part II with the statistical analyses undertaken; and Part III with a study of power plant load shifting.

The St. Louis Region Study -- Part III -- is presented here as Report C of Volume Two. It consists of a senior honors thesis for Harvard College prepared by Donald Shepard and entitled "A Load-Shifting Model to Reduce Exposure to Air Pollution Caused by Electric Power Generation".

The report is divided into five sections -- air pollution and electric power generation, elements of the load shifting model, determination of optimum solution, operating the load-shifting model, and conclusions -- in addition to the acknowledgments. Two appendices are included in addition to the appendix of Computer graphics produced.

John C. Goodrich, Editor
Cambridge, Massachusetts
April 1970

REPORT C
ST. LOUIS REGION STUDY - PART III

Table of Contents

PREFACE

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

LIST OF MAPS

ACKNOWLEDGMENTS

1. AIR POLLUTION AND ELECTRIC POWER GENERATION
    - 1.1 The Relocation of Air Pollution
        - 1.1.1 Introduction
        - 1.1.2 Approach to the Problem
    - 1.2 Air Pollution in St. Louis
        - 1.2.1 Emissions of Various Pollutants
        - 1.2.2 St. Louis Air Quality
    - 1.3 Air Pollution Meteorology
        - 1.3.1 Spread of Pollution
        - 1.3.2 Atmospheric Stability
        - 1.3.3 Special Atmospheric Conditions
    - 1.4 Electric Power
        - 1.4.1 Generating Facilities
        - 1.4.2 Fuels
        - 1.4.3 Cycles in Demand for Power
        - 1.4.4 Dispatching
        - 1.4.5 Interaction with Other Regions
    - 1.5 Effects of Air Pollution Exposure
        - 1.5.1 An Economist's Viewpoint
        - 1.5.2 Empirical Effects

2. ELEMENTS OF THE LOAD-SHIFTING MODEL
    - 2.1 Introduction
    - 2.2 Population Densities and the Power Plant Study Region
        - 2.2.1 The Power Plant Study Region
        - 2.2.2 Projected 1970 Population Densities
        - 2.2.3 Conversion of Population Densities to a Regular Grid
    - 2.3 Plume Rise and SO_2 Emission Parameters
        - 2.3.1 SO_2 Emissions

TABLE OF CONTENTS (Cont'd)

2.3.2 Plume Rise Adjustments

2.4 Adaptation of a Dispersion Model
2.4.1 The Gaussian Diffusion Equation
2.4.2 Limited Mixing Depth
2.4.3 Cross-Wind Diffusion
2.4.4 Instantaneous Wind Directions
2.4.5 Vertical Diffusion
2.4.6 Wind Speeds at Plume Height
2.4.7 Effective Stack Height

2.5 Cost Functions
2.5.1 Fuel Cost
2.5.2 Sulfur Dioxide Exposure Cost
2.5.3 Combined Cost

3. DETERMINATION OF OPTIMUM SOLUTION

3.1 Statement of the Problem

3.2 Restatement of Cost Functions
3.2.1 Piecewise Linear Approximation
3.2.2 Treatment of Declining Absolute Costs -
3.2.3 Reduction in Number of Linear Segments -
3.2.4 Formulation as Mixed-Integer Programming Problem
3.2.5 An Efficient Constraint Matrix

3.3 Analysis of Mixed-Integer Programming

4. OPERATING THE LOAD-SHIFTING MODEL

4.1 Reason for Solving the Model

4.2 Case 1 - Moderate Southerly Wind
4.2.1 Required Data
4.2.2 Assumptions on Load and Outages
4.2.3 Discussion of Numerical Results
4.2.4 Discussion of Graphical Results
4.2.5 Analysis of Results
4.2.6 Problem 2, a Holiday

4.3 Case 2 - Light Westerly Wind
4.3.1 Meteorological Conditions
4.3.2 Graphical Discussion of Results
4.3.3 Numerical Analysis of Results

TABLE OF CONTENTS (Cont'd)

4.4 Case 3
  4.4.1 Results under Control of Sulfur Oxide Emissions
  4.4.2 Trade-off Between Fuel and Exposure Costs

5. CONCLUSIONS

5.1 Sensitivity of the Model
  5.1.1 Sensitivity to Meteorological Factors --
  5.1.2 Sensitivity to Power Demand

5.2 General Evaluation of the Model

5.3 Applications
  5.3.1 Daily Operation
  5.3.2 Conceptual Applications
  5.3.3 Evaluation of Investments
  5.3.4 Applications to Other Industries

REFERENCES

APPENDIX A: OPTIMAL LOAD DISPATCHING AND COSTS FOR ST. LOUIS POWER PLANTS

APPENDIX B:
  B.1 Computer Mapping Routine "SYMAP"

  B.2 Costs and Emission Rates Under Various Control Practices

APPENDIX C: COMPUTER GRAPHICS

LIST OF ILLUSTRATIONS

Figure Page

CHAPTER 1

1-1 Atmospheric Lapse Rates and Stability --------------- 11
1-2 Typical Daytime Temperature Profile over Urban Area - 13
1-3 Typical Nighttime Inversion over Urbanized Area ----- 13a
1-4 Plume Behavior in Unstable Atmosphere Beneath Inversion Lid ------------------------------------ 15
1-5 Plume Behavior in Stable Atmosphere above Inversion Lid --- 16

CHAPTER 2

2-1 Generalized Flow Chart for Load-Shifting Model ------ 30
2-2 Graph of Relative Heat Efficiency as a Function of P/P_o -- 44
2-3 Graph of Probability Distribution $f_1 (\eta|\phi)$ ---------- 53
2-4 Graph of Probability Distribution $f_2 (\theta|\eta)$ ---------- 54
2-5 Graph of Probability Distribution $f^2(\theta|\phi)$ and of Normal Distribution with Same Variance, for b = (10/11.25)a ------------------------------------ 58
2-6 Graph of fuel and Maintenance Costs for Meramec Unit 4, 1970 -- 72
2-7 Graph of Total Air Pollution Exposure for Meramec Unit 4, Meteorological Case 1 ---------------------- 77
2-8 Graph of Combined Cost Function for Meramec Unit 4, Meteorological Case 1 ------------------------------ 78

CHAPTER 3

3-1 Graph of Simplified Combined Cost Function for Meramec Unit 4, Meteorological Case 1 --------------- 87
3-2 Primary and Secondary Vertices, and Slack Variables on Hypothetical Simplified Combined-Cost Function -- 91a

CHAPTER 4

4-1 Cost Curve Trade-off Between Fuel Cost and Air Pollution Exposure (Case 3, Problem 2, Based on Table 4-5) --- 120

LIST OF TABLES

Table Page

CHAPTER 1

1-1 Electric Power Load for Selected Days at Highest, Lowest and Average Hour, Union Electric Company 21

CHAPTER 2

2-1 Initial Stack, Fuel, Heat, and Emission Data for Major Steam-Electric Generating Units 41
2-2 Coordinates, Final Emission Rates, Capacities, Plume Rise Parameters, and Ratio of Net to Gross Capacity, St. Louis Area Dispatching Units, 1970 47
2-3 Variability of Instantaneous Wind Direction by Stability Classes 56
2-4 Variance and Standard Deviation of Instantaneous Wind Variability According to Parameter b 59
2-5 Cross-Wind Diffusion Parameters 61
2-6 Parameters for Vertical Diffusion from Martin-Tikvart Model 63
2-7 Representative Incremental Cost Schedules 70

CHAPTER 4

4-1 Case 1 - Moderate Southerly Wind, Distribution of Meteorological Parameters 97
4-2 Summary Statistics: Total Fuel Costs and SO_2 Pollution Exposure under Optimal Dispatching, Case 1 - Moderate Southerly Wind 108
4-3 Case 2 - Light Westerly Wind, Distribution of Meteorological Parameters 112
4-4 Summary Statistics: Total Fuel Costs and SO_2 Pollution Exposure under Optimal Dispatching, Case 2 - Light Westerly Wind, Normal Coal 115
4-5 Summary Statistics: Total Fuel Costs and SO_2 Pollution Exposure under Optimal Dispatching, Case 3 - Light Westerly Wind 117

LIST OF TABLES (Cont'd)

Table | Page

APPENDIX A

A-1 Optimal Load Dispatching and Costs for St. Louis Power Plants, Dispersion Case 1, Problem 1 A-1
A-2 Optimal Load Dispatching, Case 1, Problem 2 A-2
A-3 Optimal Load Dispatching, Case 2, Problem 1 A-3
A-4 Optimal Load Dispatching, Case 2, Problem 2 A-4
A-5 Optimal Load Dispatching, Case 3, Problem 1 A-5
A-6 Optimal Load Dispatching, Case 3, Problem 2(a) & (b) A-6
A-7 Optimal Load Dispatching, Case 3, Problem 2(c) & (d) A-7

APPENDIX B

B-1 Cost Ratio, Emission Ratio, and Process Used for Limiting Sulfur Oxide Emissions B-5

LIST OF MAPS

Map No. Title

C-1 Sulfur dioxide concentrations in ppm--moderate wind from the South
Average of 2-hr. readings--Friday, Jan. 22, 1965
Actual air quality (40 receptors)

C-2 Population density, projected 1970, population per square mile
Based on 1960 census tracts and 1970 county projections by
The East-West Gateway Coordinating Council, St. Louis area

C-3 Population density, projected 1970, population per square mile
Based on 1960 census tracts and 1970 county projections by
The East-West Gateway Coordinating Council, St. Louis area by grid

C-4 Sulfur dioxide concentrations under dispatching without regard to "social cost", parts per hundred million.
Using diffusion model with moderate wind from the South, Neutral stability
[For Case 1, Problem 1(b), Concentrations]

C-5 Sulfur dioxide concentrations for minimal exposure--St. Louis, pphm, based on optimal dispatching of electric power stations, 1970; using diffusion model with moderate wind from the South, neutral stability
[For Case 1, Problem 1(a), Concentrations]

C-6 Improvement in air pollution resulting from "social cost" dispatching. Sulfur dioxide concentrations in parts per hundred million, using diffusion model with moderate wind from the South, neutral stability
[For Case 1, Problem 1(b) minus 1(a), Concentrations]

C-7 Density of exposure to pollution under dispatching without regard to "social costs"--person parts per million per sq. mile, using diffusion model with moderate wind from the South, 3000 mw load
[For Case 1, Problem 1(b), Exposure]

C-8 Optimal dispatching density of exposure to SO_2, St. Louis area 1970--population density x SO_2 concentration, person-ppm SO_2 per sq. mile, using diffuison model with moderate wind from the South, 3000 mw load
[For Case 1, Problem 1(a), Exposure]

C-9 Improvement in population exposure due to "social cost" dispatching--population density x SO_2 concentration, person-ppm SO_2 per sq. mile, using diffusion model with moderate wind from the South, 3000 mw load
(For Case 1, Problem 1(b) minus 1(a), Exposure]

C-10 Sulfur dioxide concentrations under dispatching without regard to "social cost", parts per hundred million, using diffusion model with light wind from West, unstable, 2000 mw load
[For Case 2, Problem 2(b), Concentrations]

C-11 Sulfur dioxide concentrations for minimal exposure--St. Louis, pphm, based on optimal dispatching of electric power stations, 1970, using diffusion model with light wind from West, unstable, 2000 mw
[For Case 2, Problem 2(a), Concentrations]

C-12 Improvement in air pollution resulting from "social cost" dispatching sulfur dioxide concentrations in parts per hundred million, using diffusion model with light wind from West, unstable, 2000 mw
[For Case 2, Problem 2(b) minus 2(a), Concentrations]

C-13 Density of exposure to pollution under dispatching without regard to "social costs"--person parts per million per sq. mile, using diffusion model with light wind from West, unstable, 2000 mw
[For Case 2, Problem 2(b), Exposure]

C-14 Optimal dispatching density of exposure to SO_2, St. Louis area 1970--population density x SO_2 concentration, person-ppm SO_2 per sq. mile, using diffusion model with light wind from West, unstable, 2000 mw
[For Case 2, Problem 2(a), Exposure]

C-15 Improvement in population exposure due to "social cost" dispatching--population density x SO_2 concentration, person-ppm SO_2 per sq. mile, using diffusion model with light wind from West, unstable, 2000 mw
[For Case 2, Problem 2(b) minus 2(a), Exposure]

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Donald S. Shepard
June 1, 1969

A LOAD-SHIFTING MODEL TO REDUCE EXPOSURE TO AIR POLLUTION CAUSED BY ELECTRIC POWER GENERATION

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CHAPTER 1

AIR POLLUTION AND ELECTRIC POWER GENERATION

1.1 THE RELOCATION OF AIR POLLUTION

1.1.1 Introduction

This paper describes the construction and evaluation of a mathematical model to reduce exposure to air pollution from the generation of electric power. Although electricity is generally not associated with air pollution, the burning of bituminous coal and residual fuel oil in steam-electric power generating plants produces a huge volume of air pollution every hour, despite certain control measures already in use.

This paper presents a novel approach to control: changing primarily the location, rather than the amount of air pollution, so as to make it less objectionable. The study assumes that for economic or technical reasons it is not possible to reduce the pollution emissions beyond a certain level and that the most immediate short term abatement can be controlling the location of atmospheric concentrations. Generally speaking, air pollution in the United States is an urban problem. Accordingly, this study will focus on air pollution in a metropolitan area. Although air pollution does not respect political borders, to a large extent it respects distance: the air pollution problems of non-adjacent metropolitan areas at least 50 miles apart may generally be considered separately. This paper will concentrate on the St. Louis, Missouri metropolitan area, in order to benefit from a particularly intensive research study conducted on that area[26].

Although it is possible for electricity to be transmitted economically across several states, the plans of the electric utility companies in the St. Louis area are such that most of the electric power needs of the area will continue to be met by fossil fuel burning plants within fifty miles of the St. Louis Gateway Arch.

Until a technology absolutely free of any air pollution comes into universal use in St. Louis, electric power generation will remain, to some extent, a pollution problem. Concurrent with the goal of reducing emission rates to a level economically and technically feasible, should stand the goal of putting this remaining pollution in a place where it will be of least harm to the public.

In one sense, man cannot control the geographical distribution of pollution; once released into the atmosphere, wind and turbulence control its transport. In another sense, though, man can control its location by choosing where to release the pollution, assuming that it must be released somewhere. In electric power generation this locational choice is of particular interest.

In St. Louis, as in most metropolitan areas, electric power is generated mainly in fossil fuel plants around the metropolitan area. But unlike many industrial plants, the principal output from one plant--60 cycle a.c. electric power--is immediately interchangeable with that from another. I assume that the technology embodied in existing facilities is such that the electric power demands cannot be met without emitting some air pollution(1).

Thus, careful choice of which generating plants to use can serve to minimize the spread of pollution to areas where it is considered most harmful. Relocation of air pollution has the advantage of offering a three-dimensional space into which the pollution might be guided. Not only is geographic location of interest, but also the altitude; it is generally ground-level concentrations with which people, materials, and vegetation come into contact. This study of the St. Louis area will be concerned with seven major coal-burning plants to be in operation, 1970. Of these, three are located within four miles of downtown St. Louis, and the remaining four from twenty to forty miles south, west, or north of the Gateway Arch.

1.1.2 Approach to the Problem

Provided demand for electricity is not so heavy as to require all plants to operate at full capacity, there is a choice of deciding which power plants to operate and at what levels. Altering the load on power plants to reflect air pollution considerations will be termed load shifting. In this paper, I am concerned with total exposure to air pollution, which will be the sum of the concentrations of one pollutant, sulfur dioxide, in various "zones", times the number of people in each zone. But I am also concerned with economics: there is a cost to reducing air pollution to be matched against the probable savings and benefits from its reduction.

---

(1) Present commercial plants, which will not all be scrapped or be modified to reduce all pollution in the near future, certainly meet this assumption.

In this first chapter, I shall introduce various concepts on air pollution meteorology and the air pollution problem in St. Louis to put this model in perspective. In chapter two I will develop three cost functions--a fuel cost function, an exposure cost function, and a combined cost function (air pollution plus fuel costs) for each group of generating units in the St. Louis area, representing the private, social, and combined costs of operating a generating unit at any level of output. Chapter three will present a procedure for finding the optimum load shifting solution through mixed integer programming, and for evaluating the results. In chapter four, the model is actually operated and evaluated under two typical meteorological conditions. For the south wind case, it will be seen that the load-shifting model responds vigorously with little increase in fuel costs. For the west wind case, the locations of power plants is less favorable and the results will be less dramatic, though still significant. Finally, case 3 will show that moderate improvements in pollution exposure can be obtained from load shifting even above those achieved through low sulfur coal or stack gas cleaning. An operational outline for load shifting in St. Louis is beyond the scope of this paper. Rather it is a demonstration of the feasibility of load shifting--to show that large to moderate reductions in population exposure to air pollution may be obtained under many meteorological conditions without a large increase in the cost of generating electric power.

1.2 AIR POLLUTION IN ST. LOUIS

1.2.1 Emissions of Various Pollutants

The St. Louis area(2) has been ranked between sixth to tenth in the country in terms of its air pollution severity. The emission of pollutants in St. Louis resembles the national estimates in that the most common type of pollution, in terms of tons per year, is carbon monoxide, which accounts for 65 of the estimated 125 tons of pollution poured annually into the atmosphere (1967). About 80% of carbon monoxide emissions are from transportation (combustion engines), and only 0.1% from steam-electric power generation; therefore, this paper will not consider carbon monoxide emissions.

Second, in terms of annual tonnage emissions, are sulfur oxides--SO_2 and its decomposition products, and third are particulates (fine particles). Steam-electric generation accounts for 55% of the annual sulfur oxides emissions of 662,300 tons in the St. Louis area, and almost 30% of the 175,600 tons of annual particulate emissions([34], p. 19). It also accounts for about 40% of the estimated 181,000 tons of nitrogen oxides emitted annually in the area([28], p. 10). Nitrogen oxides are thought to react with hydrocarbons (incompletely burned gasoline and industrial process emissions) to produce brownish smog. Particulates (fine bits of ash, sometimes smaller than 1 micron) are partly responsible for urban hazes and act as a catalyst in the transformation of sulfur dioxide into the more potent sulfuric acid mist, and in corrosion of material and irritation of the human respiratory system.

---

(2) Includes St. Louis City, St. Louis, Jefferson, and Franklin counties, Missouri; Madison, St. Clair, and Monroe, Illinois.

Since this study is concerned with the effects of power plants on population exposure to air pollution, it will focus on sulfur dioxide. Not only is this the pollutant for which electric power generation has the greatest responsibility, but also it is the most fully researched and measured pollutant. Many health effects are empirically linked to it, alone or in the presence of particulates.

Indirectly, the synergism of particulates and sulfur oxides will be considered, since coal burning power plants emit particulates in addition to sulfur oxides. And though the major power plants in the St. Louis area are equipped with electrostatic precipitators of 90 to 99% efficiency (as measured in terms of mass reduction of particulates emitted), these devices are least efficient for the smallest particulates (less than 1 micron diameter) which remain in the atmosphere longest, are of a size to become trapped in alveoli of the lungs, and have the greatest surface to mass ratio, and hence the greatest potency as a catalyst for corrosive reactions. All of these considerations are implicit, however, because neither sulfur oxide nor particulate concentrations from sources other than power plants were estimated, nor were the emissions of particulates of various diameters from each plant. Since I shall derive a damage function I consider plausible, but certainly not definitive, the added complication of considering many pollutants would be unwarranted.

The unanswered questions about sulfur dioxide are an indication of the number of questions still unanswered about all pollutants. A more elaborate study might look at the contribution of each power plant to the combined concentrations of nitrogen oxides, particulates and sulfur oxides, and the "damage" of any particular combination. A student of economics[22] has set up the framework for such a study by industries in the St. Louis area, but the geographic factor of emissions is not considered.

1.2.2 St. Louis Air Quality

Although sources of pollution other than power plants will not be considered explicitly, it will help the reader to appreciate the magnitude of expected reductions from this model if he can compare them with some reference levels. For this purpose, Map C-1 is included to show air quality on a particular winter day. The wind oscillated between S and SE, and averaged about 12 mph over the 24 hour period. The high concentrations stretching northwest from downtown indicate that pollution concentrations are definitely affected by the wind. The maximum concentration of sulfur dioxide is about 9 pphm (24 hour average), a fairly high level. The SYMAP computer mapping procedure on which this map is based is described in greater detail in appendix B.1, and section 2.2.2. On this map, data point locations are denoted by asterisks and the rivers by vertical bars. It is clear that all forty receptor locations were in the inner part of the metropolitan region, and that it is not meaningful to draw a map in an area without data. By means of an elective in the SYMAP program, any print location more than a specified distance (25,000 feet) from all data points was left blank.

1.3 AIR POLLUTION METEOROLOGY

1.3.1 Spread of Pollution

To understand the geographical distribution of air pollution, one must know something about the factors governing the spread of pollution from its original point of emission.

First, in this paper I shall be primarily concerned with the gas, sulfur dioxide, SO_2. Surprisingly little is known about its cycle through the atmosphere, though it appears to be oxidized after a few hours to sulfur trioxide, and reacts quickly with moisture in the air to form a dilute sulfuric acid mist or combine with particles in the atmosphere to become soluble sulfates. Apparently, rainfall washes most of the sulfur dioxide and its decomposition products from the atmosphere.

Should the initial concentration be high, then the rain will be acidic and damaging to vegetation, but otherwise no residual effect is known from this cleaning.

Deposition--namely adherence of the gas, mist, or sulfate to some object with which it comes in contact--is another means by which the pollution is purged from the air. The stages in this process where the pollution may be most damaging to people and materials is as SO_2, initially, and as dilute acid mist.

Pollution from combustion sources such as power plants are emitted at, or within, a few hundred meters of ground level. Once emitted, there is relatively little lateral motion with respect to the surrounding air, so the most important factor is the downwind transport of pollution. There is some vertical motion. First, the pollutant may be mixed in the hot exit gas of a stack, and will rise above the stack for some distance due to momentum and buoyancy (the gas is hotter than the surrounding air). The exact amount the gas rises above the stack, called the plume rise, will be discussed later. At the altitude to which the plume finally rises, vertical diffusion of polluted plume gases has begun; the plume is diluted and the pollution reaches ground level in increasing quantities as it is carried downwind.

1.3.2 Atmospheric Stability

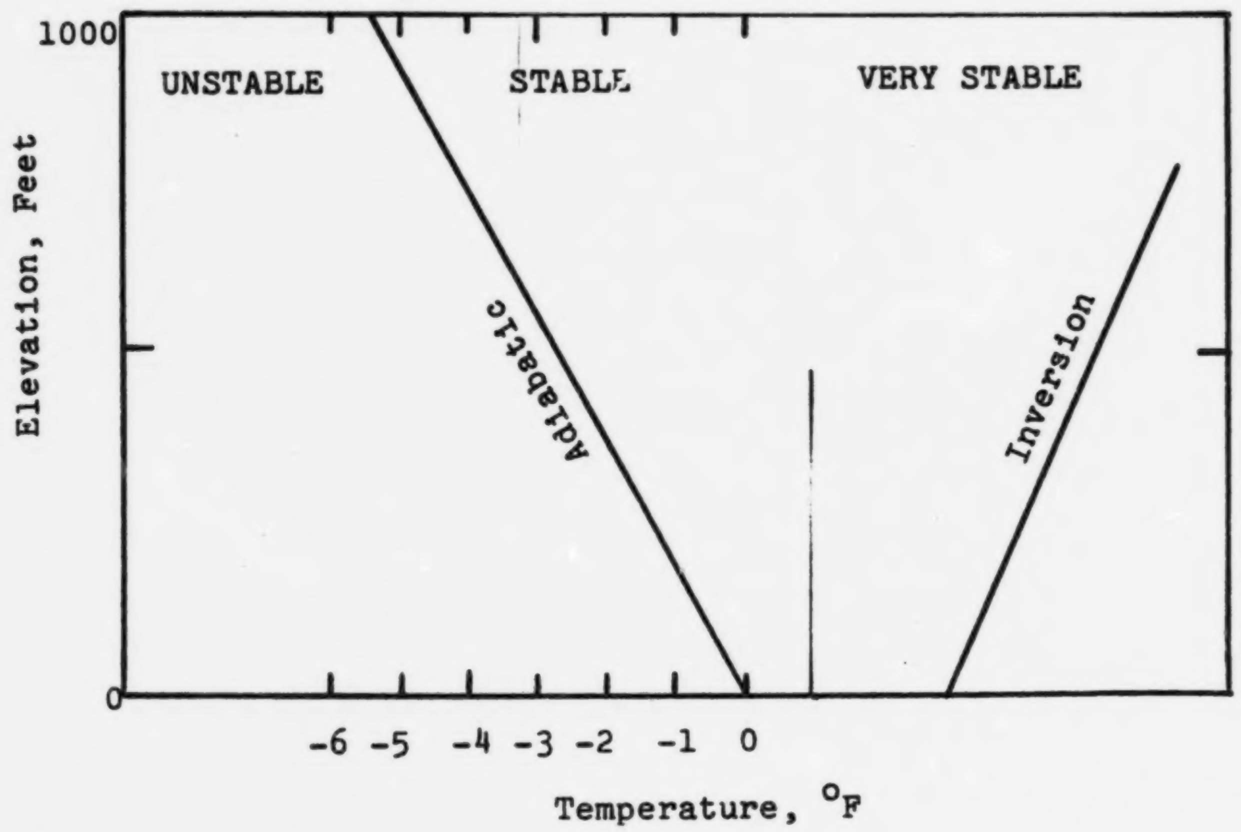
The exact amount of vertical spreading depends upon an atmospheric parameter called stability. Because of the change of pressure with altitude, a rising parcel of air will cool by 0.98°C per 100 m rise (or warm by an equal amount for a 100 m. decline) if it does not exchange heat with its surroundings. With data from weather balloons, the actual gradient of temperature with altitude, or lapse rate, may be measured. As shown in Figure 1-1 (based on Figure 1, Vol. V, p. 2[26]), the actual decline in temperature with altitude may be greater or less than the adiabatic (no heat flow) lapse rate. If greater, then a parcel of gas initially in equilibrium with the surrounding air will be warmer after rising, and hence will tend to rise further. If, on the other hand, it falls initially, it will not warm as quickly as the surrounding air. Being cooler and hence heavier than the surrounding air, it will tend to rise or fall still further. When the temperature decline with increased altitude is greater than the adiabatic lapse rate, the atmosphere is termed unstable. It is conducive to the forming of eddy currents and the wide dispersal of pollutants. Such conditions are most frequent on sunny days, when the ground and the air near it, are strongly heated.

On the other hand, the lapse rate may be less negative than the adiabatic lapse rate. A parcel of air which rises will tend to be cooler than the surrounding atmosphere and return to

FIGURE 1-1

ATMOSPHERIC LAPSE RATES

AND STABILITY



its original altitude. Such an atmosphere is called stable and inhibits the vertical spreading of pollution. Overcast, early morning, and late evening conditions are often of this type. Finally, the temperature may increase with height in what is termed a temperature inversion (the lapse rate is the reverse of the adiabatic lapse rate), and spreading of pollution is particularly inhibited. Ground-based temperature inversions occur on almost every clear night, for the ground and air near it cool more rapidly than the air aloft.

A typical daytime temperature profile such as Figure 1-2 is a combination of two or three conditions. For the first few hundred meters, the atmosphere is stable or neutral, due to heating from the earth's surface. At some height, termed the mixing depth, a warmer air mass may be entered, or the lapse rate from the nighttime ground-based inversion will still prevail, so there will be an inversion aloft. At some distance above it, the atmosphere may become neutral. For St. Louis, the average maximum mixing depth is 490 meters in January, with a standard deviation of about 250 m([26], vol. 5, p. 10, Figure 17, based on [20]). An estimated nighttime temperature profile is shown in Figure 1-3 for an urbanized area like St. Louis in winter. Because of heat from buildings, the inversion is based about 100 m aloft.

The height of the inversion is of critical importance to air pollution, for it acts as a lid. So long as the condition prevails, pollution emitted near the ground especially, or anywhere

FIGURE 1-2

TYPICAL DAYTIME TEMPERATURE PROFILE
OVER URBAN AREA

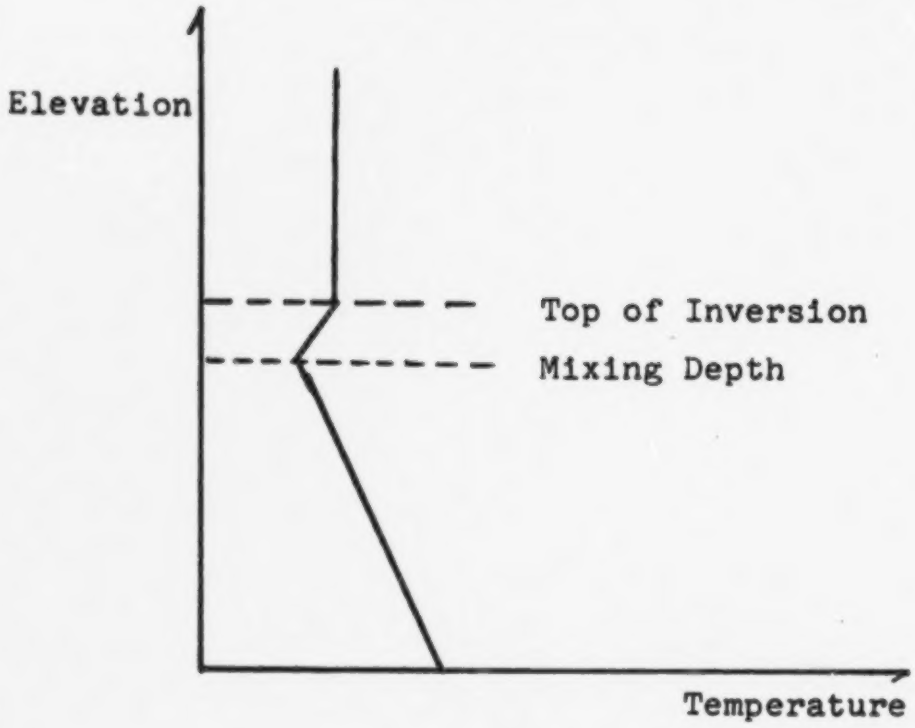
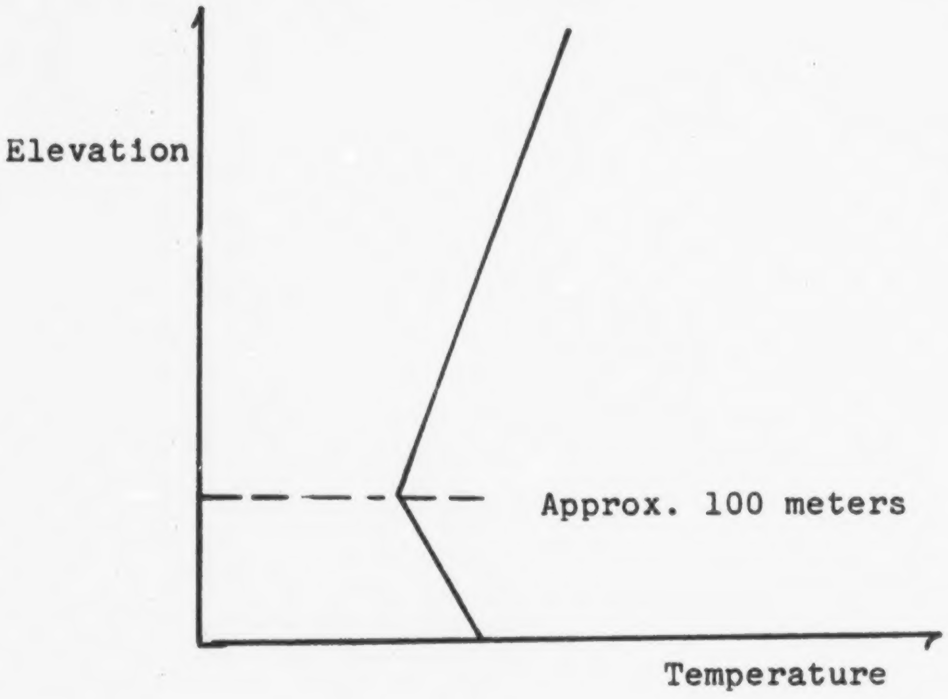

Elevation
Top of Inversion
Mixing Depth
Temperature

FIGURE 1-3

TYPICAL NIGHTTIME INVERSION OVER URBANIZED AREA


Elevation
Approx. 100 meters
Temperature

under the lid, is trapped in a small volume and concentrations may accumulate. But the lid also functions as a "protective barrier"[4], and once beyond it, pollution is prevented from reaching ground level.

Finally, a word should be said about horizontal or cross-wind diffusion. As a gas is carried downwind, it tends to spread horizontally due to the kinetic motion of the molecules, and the turbulence of the atmosphere. Slight variation in the wind direction means further cross-wind spreading about the mean downwind direction. Diffusion studies have measured vertical and cross-wind dispersion as functions of downwind distance and of atmosphere stability. Figure 1-4 shows the behavior of a plume in an unstable atmosphere trapped under the inversion lid. Figure 1-5 shows the same plume above the lid in a stable atmosphere (both figures are based on [26], Vol. 5, p. 4).

1.3.3 Special Atmospheric Conditions

Two important types of pollution conditions are omitted from this paper because they are extremely difficult to model accurately[41]: fumigation and subsidence inversion. Fumigation occurs in the morning with the breakup of an inversion. A plume previously trapped aloft is almost dumped into contact with the ground. Localized concentrations will be high but of less than an hour's duration. The subsidence inversion occurs when one air mass moves in above another. It may accompany a stagnating anticyclone, and is responsible for prolonged periods of serious air pollution, such as the 1966 Thanksgiving weekend

FIGURE 1-4

PLUME BEHAVIOR IN UNSTABLE ATMOSPHERE
BENEATH INVERSION LID

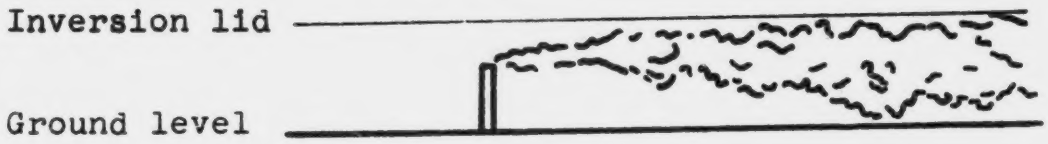
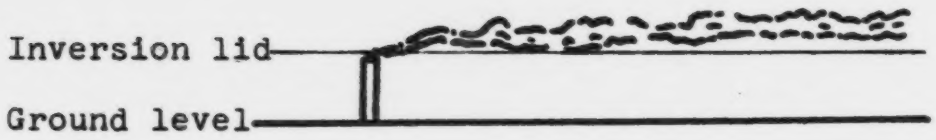

Inversion lid
Ground level

FIGURE 1-5

PLUME BEHAVIOR IN STABLE ATMOSPHERE
ABOVE INVERSION LID


Inversion lid
Ground level

episode which covered the East Coast. Such conditions, however, are less frequent in St. Louis than in the East[21]. A load-shifting model to deal particularly with "incidents" of high concentration, lasting perhaps for days, would need a dispersion model taking into account the accumulation of pollution which causes such incidents.

1.4 ELECTRIC POWER

1.4.1 Generating Facilities

Before I discuss how the electric power industry can reduce its additions to air pollution exposure in St. Louis, I should first describe briefly relevant aspects of the industry in St. Louis.

The St. Louis Power Plant Study Region with an estimated 1970 population of about 2.7 million people is served by two major electric power companies--Illinois Power Company and Union Electric Company, and one small one--Highland Electric Light Co. The single Highland plant will be excluded from this study for simplicity because of its very small size--50 mw, and because of its location at the periphery of the region(3). Union Electric and Illinois Power are connected directly together and sell power regularly. In addition, Union Electric belongs to various exchange pools such as the Illinois-Missouri pool for buying and selling power on a regular basis and meeting reserve power needs.

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(3) Economies of scale are such in the operation of power plants that the Highland Plant probably would not be operated, air pollution aside, if power could be obtained elsewhere.

The economics of electric power generation varies with fuel availabilities from one region of the country to another. In Boston, for example, residual fuel oil is used primarily and nuclear power plants are being constructed or already in operation. In the Los Angeles area, most generation is done with natural gas. St. Louis, on the other hand, relies on coal and natural gas from mid-spring to mid-fall, and almost entirely on coal in the winter when gas is not available[29]. In addition, the Union Electric company has two hydroelectric facilities (Keokuk and Osage) and a pumped-storage plant (Taum Sauk) which uses power at night to pump water into an elevated storage reservoir, and can obtain power during peak day demand periods by letting the water run out past generator turbines. Since the Osage dam has some storage capacity, this facility may also be used more intensively during peak periods of the day.

1.4.2 Fuels

Power plants in the St. Louis area generally burn coal of about 3% sulfur content (by weight). Upon combustion, the sulfur oxidizes primarily to SO_2, though some to SO_3. Generally about 95% of the sulfur in coal is emitted as SO_2, so a ton of 3% sulfur coal releases 114 lb. SO_2. Several of the coal-burning units are also equipped for natural gas, and generally use it instead of coal in the summer. In winter, however, natural gas would not be available at all, or only at prohibitive prices for electric power generation[29]. Combustion of a ton of coal also emits an estimated 20 lbs. nitrogen oxides (NO_4). Particulate emissions vary with the type of control equipment.

Emissions of sulfur dioxide from natural gas are negligible. Residual oil burned in the St. Louis area contains 2% to 2.5% sulfur by weight.

1.4.3 Cycles in Demand for Power

Electric power is an unusual type of energy in that it cannot be stored in significant quantities. And, except in unusual or extreme emergency circumstances, electric power to a particular group of users cannot be suddenly curtailed(4). Thus the seasonal and daily cycles of power demand is of critical importance for the operation of an electric power system and the resulting air pollution.

In St. Louis the season of heaviest demand for electricity is the summer. Temperatures in the nineties are not then unusual, and air conditioning is required. This pattern actually presents advantages from the point of air pollution. The heavy sulfur oxide load from electric power generation is counterbalanced by the virtual absence of space heating in many small furnaces. Also, the summer mixing depth is higher and the atmosphere less stable than in winter.

In winter, when air pollution is worse due to space heating and lower mixing depth, it may be possible to further reductions in pollution exposure through the load-shifting method I am outlining. At present, most of the excess winter capacity is in the form of older plants located in the center of the region, which create high air pollution exposures. However, with the opening of Labadie units in 1970, there should be sufficient flexibility that air pollution can be considered in meeting demands.

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(4) Some large industrial power users may have "interruptible load" contracts under which they could be, if necessary, cut off from the system. Procedures also exist for "load shedding" in case of major system failures to prevent a total blackout.

The diurnal variation of power demand is of about the same magnitude as the seasonal variation--about a 50% increase from minimum to maximum hour. Late afternoon generally brings the highest power demands, so again, during other times of the day excess capacity exists. Furthermore, because most businesses and industries are closed on Sundays and holidays, these days have lower load requirements than weekdays. Table 1-1 shows typical variations in power demand with season, hour, and day of the week for the Union Electric Company, operator of six of the seven plants in the St. Louis PPSR.

1.4.4 Dispatching

Almost never will all available generating units in an electric power system need to be operated at full capacity. Knowing the demand for electricity at a particular hour, someone must decide which units are to generate electric power, and how much, to meet the load--a process called load dispatching. At present, one major consideration is economics. The required net power should be generated at the least possible cost. Because electric generators are generally less efficient, in terms of fuel usage, at highest output, marginal costs tend to increase on each unit. Least cost dispatching means finding a solution

TABLE 1-1

ELECTRIC POWER LOAD FOR SELECTED DAYS AT HIGHEST, LOWEST AND AVERAGE HOUR UNION ELECTRIC COMPANY[43]

Day	Hourly Load, mw		
	Highest Hour	Lowest Hour	Average Hour
Late Fall Weekday (Wednesday, 11/27/68)	2472 6 p.m.	1507 4 a.m.	2085[a]
Late Fall Holiday (Thanksgiving, 11/28/68)	1823 12 noon	1402 5 a.m.	1645[b]
Summer Weekday (Monday, 7/22/68)	3591 4 p.m.	1917 5 a.m.	2903[a]

NOTES:

[a] from 24-hour integrated total load

[b] from selected hourly loads

in which all the marginal costs are equal.

In practice other factors must also be considered--which plants are already in operation, or will be needed in a few hours to meet a peak, and how fast the boilers may be heated. In addition, there are the problems of reliability and of a "running reserve" requirement, meaning that the generating units already operating must have sufficient excess capacity so as to be able to meet a small increase in load immediately. When factors of hydroelectric dispatching are also considered, the problem further grows(5).

Although dispatching of power plants in response to a number of requirements to generate power at the lowest possible cost is a complicated question, if the "cost" of air pollution could also be included, there would be little conceptual difficulty in including its minimization among the dispatching objectives. This degree of flexibility already built into the power system would render a load-shifting model readily operable.

The two hydroelectric units serving the PPSR not only produce no pollution, but also have very low operating costs. Thus they should continue to be used as intensively as possible. The problems of deciding when to use the limited amount of water available at Osage and when to generate or pump at Taum Sauk are complicated questions, but secondary to this study.

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(5) Therefore, the Union Electric Company uses a "Prodiac" computer to plan the least cost for dispatching.

To simplify this discussion of the load-shifting model, I will assume that these non-polluting units can operate at the same level in 1970 as they did during corresponding months in 1967-68, the period for which I have data; then their net output or demand will be subtracted or added in computing total system load on steam-electric units. Finally, the oil-burning Mound and Venice 1 plants will be excluded because they would not be operated except under the most extreme conditions. Generating with residual oil costs about twice as much as with coal in the St. Louis area, and the high sulfur content of the imported oil means little or no advantage, in terms of air pollution emissions. Lastly, the rather central location of the oil-burning plants means that their air pollution emissions would affect densely populated regions. The oil-burning units of a plant which also burns coal, Cahokia, were included so the model could indicate the need to dispatch the high-priced oil-fueled plants(6).

1.4.5 Interaction With Other Regions

Throughout this discussion, the electric power industry of St. Louis has been treated as if it were entirely insular. Since the Illinois Power Company has many plants and customers outside of the St. Louis area, and since Union Electric has bought power from other utilities almost continually in 1968, this is certainly an oversimplification. On the other hand, it would be a near-sighted result to suggest that a company halt all generating electricity within the metropolitan area and buy power from other companies, for this would only ameliorate the air pollution levels in one city at the expense of those in another(7). Even with sales, there will generally be some net demand to be met by steam-electric power plants in the study area. It is with this demand that this study is concerned. In later estimating typical loads for the St. Louis area, it will be assumed that no power is being bought from, or sold to, other regions. This load-shifting model will compute a shadow-price for power, from which the company decides whether to buy or sell power.

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(6) In the cases considered here (see chapter 4), Cahokia was not dispatched.

1.5 EFFECTS OF AIR POLLUTION EXPOSURE

1.5.1 An Economist's Viewpoint

Finally, some discussion should be given to the effects of air pollution to see why exposure should be limited. Air pollution is not solved adequately, and has become a subject of public concern because it is an example of both what an economist terms an externality, and also a public good. Air pollution is an externality because one person's pollution affects others' well being in some way without their approval. Air pollution is a "public good" because it is generally impossible for one person to have very clean air if his upwind neighbor creates dirty air.

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(7) Using an extension of this model, it should be possible to see whether less power is generated in a region, depending on how its winds compared with other cities, to minimize air pollution exposure and costs over many cities. This would be tantamount to defining a power plant study region including several cities, and adding the constraints of limited capacity and loss of power on inter-city tie lines.

Were there no wind or turbulence, each person's pollution emissions would affect himself, and himself only. Except for the matter of visibility, air pollution would then be a matter only of individual concern.

In reality, though, the atmosphere is not static, and one person's modifications of it do indeed affect another person, even though he may be up to fifty miles away (see examples in Chapter 4). When these modifications are the emission of common pollutants--sulfur dioxide, hydrocarbons, particulates, nitrogen oxides, and other gases--the effect is not beneficial. It is the purpose of this thesis to model how an industry's behavior would change if, by regulation or public pressure, it were made aware of, and economically responsible for, the air pollution "damage" it caused.

Surveys have shown ([26], Vol. VII) that the public is concerned about air pollution and would like to see it reduced. But since reduction would probably cost money, it could conflict with the "profit" goals of the industrial polluter, or "low-price" goals of the consumer. An economist can accept both the low-pollution and the low-cost wants as legitimate, and ask only that the economic system efficiency reach that balance which makes the mass of people as well-off as possible. To decide on economic grounds the proper level of cleanliness for the air would require both that some aggregate public preference function be determined, and that a curve of technical substitution between clean air and other goods be known. One outcome of this load-shifting model will be to derive some of the trade-offs between dollars spent on fuel, and reduction in air pollution exposure.

1.5.2 Empirical Effects

Field studies measuring the effect of air pollution on health, damage to vegetation and to materials are complicated undertakings, fraught with methodological difficulties. If an area has a high level of air pollution measured in terms of one pollutant, it often has a high level measured in terms of others as well; and because of possible synergistic effects, it is most difficult to write definitively about the effects of one particular pollutant. To convey to the reader some notion of the levels of pollution and kinds of effects associated, however, the following brief summary of the effects of sulfur dioxide, subject to qualifications by the researchers, is included([2], pp. 10-20, 10-22):

Man

(1) 0.25 ppm SO_2 (24 hour mean), accompanied by smoke at a concentration of 750 $\mu g/m^3$, increased daily death rate may occur (British).

(2) .11 to 0.19 ppm SO_2 (24 hour mean) with low particulates, increased hospital admissions of older persons for respiratory disease may occur; absenteeism from work, particularly with older persons may occur (Dutch).

(3) .037 to .092 ppm SO_2 (annual mean) accompanied by smoke concentrations of about 100 $\mu g/m^3$, increased frequency and severity of respiratory diseases in school children may occur (Italian).

Materials

(1) .12 ppm (annual mean) SO_2 accompanied by high particulate levels, corrosion rate for steel panels may be increased by 50% (American).

Vegetation

(1) .03 ppm SO_2 (annual mean), chronic plant injury and excessive leaf drop may occur (Canadian).

Visibility

(1) .10 ppm SO_2 with comparable concentration of particulate matter and relative humidity of 50%, visibility may be reduced to about 5 mi (American).

Several conclusions may be made about air from this tabulation: the association between air pollution (sulfur dioxide and particulate concentrations) and more frequent respiratory ailments is strongly indicated, though not conclusive([2], pp. 10-19). It is generally agreed that the health and corrosive effects of sulfur dioxide are considerably increased by the presence of particulates and sulfuric acid mist[6]. Whether sulfur dioxide or sulfuric acid mist by itself is harmful to people is a matter of disagreement and controversy. Various investigators have found a temporary increase in pulmonary flow resistance after inhalation of SO_2 alone, but these laboratory experiments are of an acute nature: the dosages generally are many times higher than those in the urban atmosphere and the time period is only an hour([2], pp. 7-4 and 7-5). Cassell's argument that sulfur oxides are harmful only in the presence of particulates has been championed by coal users who want to control particulate but not sulfur emissions. In fact, no location entirely escapes particulate concentration, for fine dust can be swept into the air from the ground or trees even in the absence of man-made pollution. It is not known whether the background particulate concentrations would be sufficiently large to catalyze the conversion to the more potent sulfuric acid mist. Furthermore, in an urban region, sulfur dioxide concentrations would invariably be accompanied by particulates. Electric power plants are harmful not only from the point of view of the sulfur dioxide they expel , but also on account of the particulates. A generating unit may burn up to 30 tons of coal per hour. And even with a precipitator of 99% efficiency, emissions of particulates will total to 30 lbs. per hour[13], composed mainly of particulates smaller than 1 micron.

CHAPTER 2

ELEMENTS OF THE LOAD-SHIFTING MODEL

2.1 INTRODUCTION

The model I propose to reduce population exposure to SO_2 through load shifting on existing power plants is really a web of several separate models, brought together and made applicable by a collection of smaller programs.

The model begins with three major types of data: (1) St. Louis population statistics; (2) air pollution emission rates for each generating unit; and (3) fuel costs for each generating unit. Figure 2-1 shows the model in broad outline. The three rather sophisticated models--the Martin-Tikvart[26] pollution dispersion model, the SYMAP computer mapping routine, and the MFOR-01-MIP mixed-integer programming package, are shown as blocks where they are used.

Each of the sections is described below in detail, indicating procedures and major assumptions. Although there are several interconnections between the types of data, I shall first discuss each separately. Secondly, the "combined" cost functions merger of each of the factors will be discussed along with the minimization procedure.

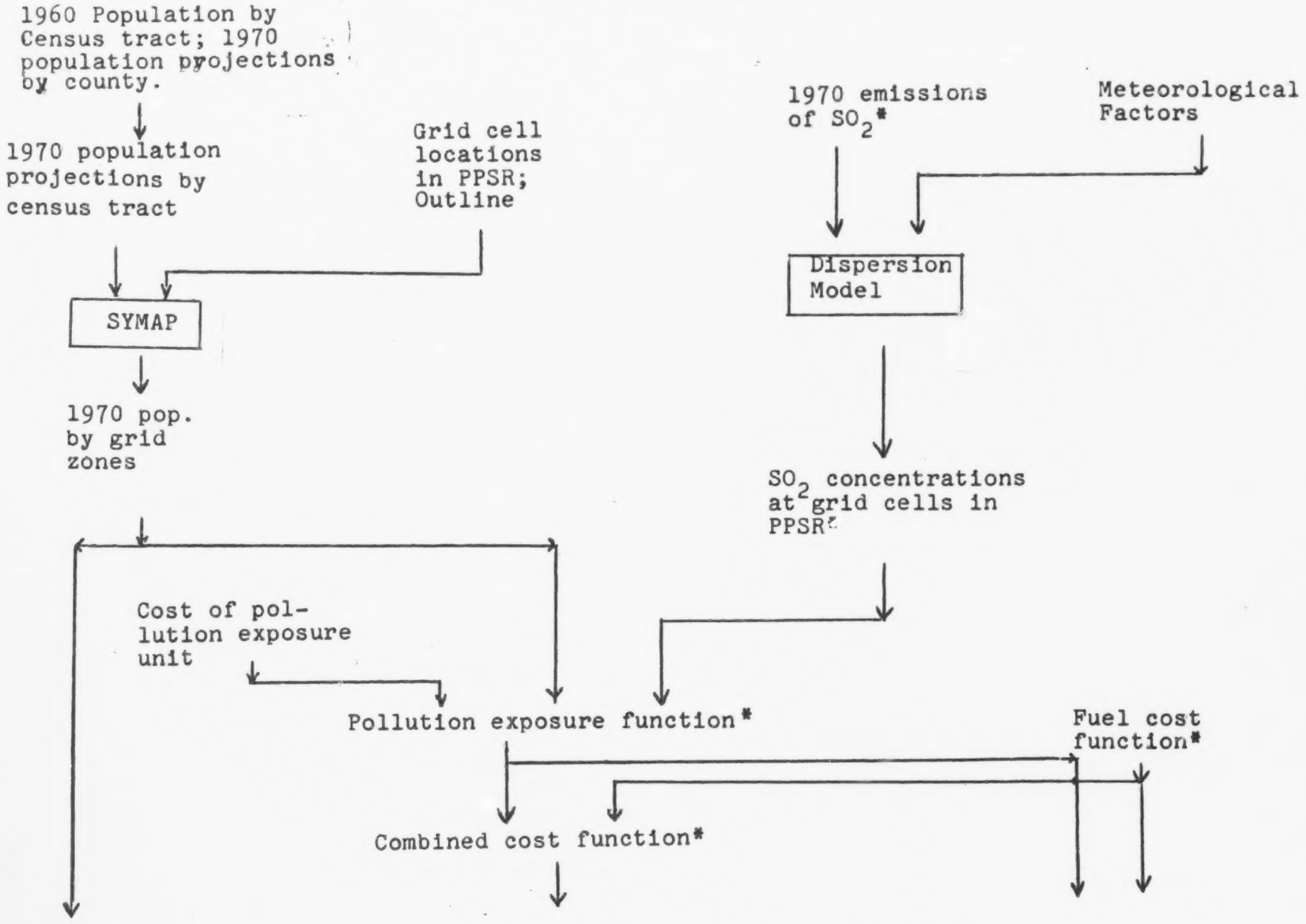
2.2 POPULATION DENSITIES AND THE POWER PLANT STUDY REGION

2.2.1 The Power Plant Study Region

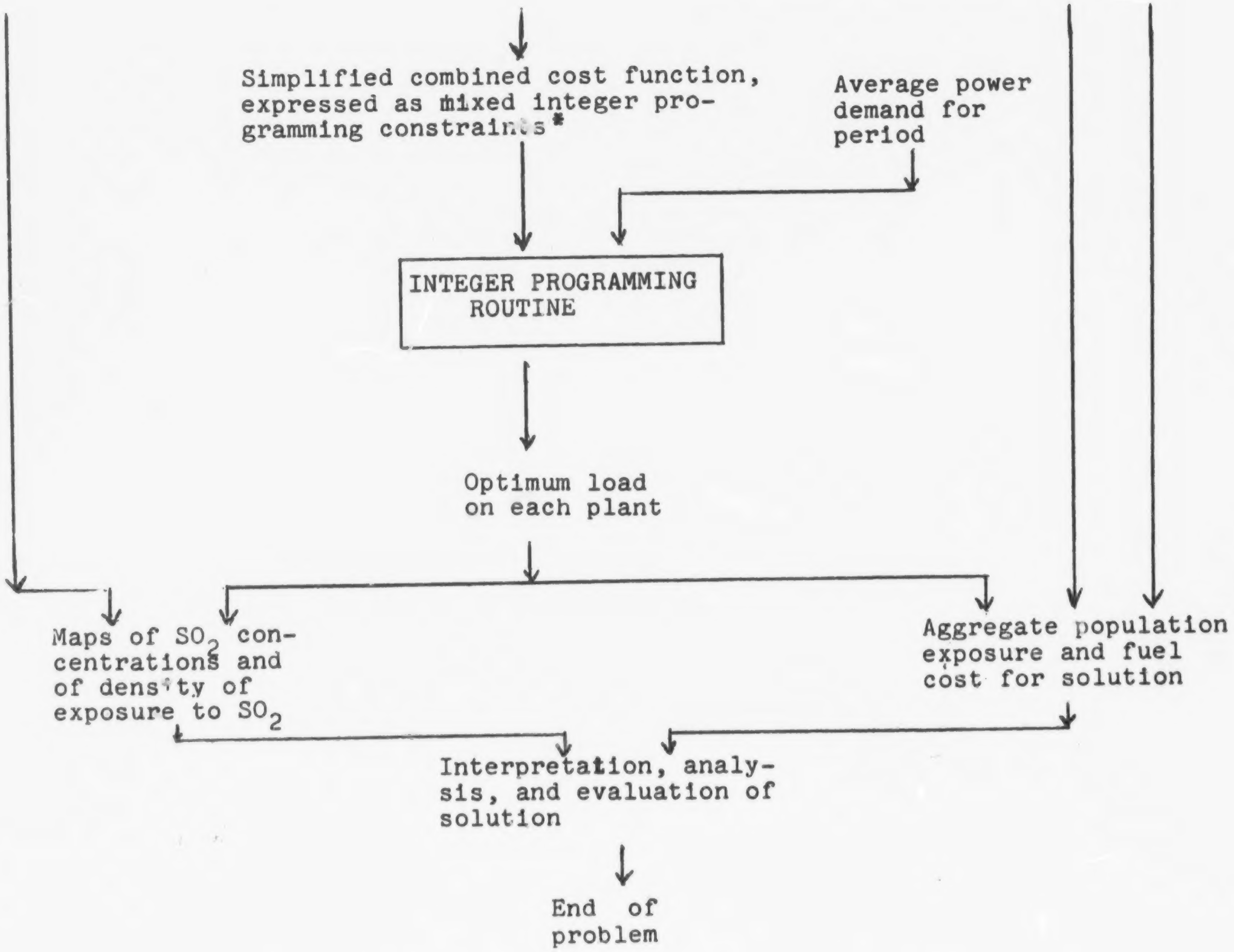
In order to minimize exposure to air pollution, it is necessary to know the spatial distribution of population in

FIGURE 2-1

GENERALIZED FLOW CHART FOR LOAD-SHIFTING MODEL


1960 Population by Census tract; 1970 population projections by county.
1970 population projections by census tract
Grid cell locations in PPSR; Outline
SYMAP
1970 pop. by grid zones
1970 emissions of SO_2*
Meteorological Factors
Dispersion Model
SO_2 concentrations at grid cells in PPSR*
Cost of pollution exposure unit
Pollution exposure function*
Fuel cost function*
Combined cost function*

[continued on following page]


Simplified combined cost function, expressed as mixed integer programming constraints*
Average power demand for period
INTEGER PROGRAMMING ROUTINE
Optimum load on each plant
Maps of SO_2 concentrations and of density of exposure to SO_2
Aggregate population exposure and fuel cost for solution
Interpretation, analysis, and evaluation of solution
End of problem

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* Indicates that calculation is performed separately for each of the 14 dispatching units in PPSR.

the St. Louis area. If the daily average sulfur dioxide concentration over a particular square mile is, say, .05 ppm(1), how many people are subjected to that dosage level?

The most comprehensive population data for the St. Louis area is the U. S. Census of population, 1960. In 1960, the St. Louis SMSA consisted of St. Louis City and the surrounding counties of St. Louis, Jefferson, and St. Charles, Missouri, and Madison and St. Clair, Illinois with a total 1960 population of approximately 2 million. For the purposes of this study concerning the effect of electric power plants on air pollution exposure, the St. Louis SMSA was considered too small an area--three major plants fell at the edge or outside of the SMSA. The air quality control region[34] proposed in accordance with the 1967 Air Quality Act adds Monroe county, but this delineation of the area still leaves two plants at edges of the region.

Rather than arbitrarily including or excluding whole counties, I chose instead to define any location within 50 km of a major steam-electric power plant as belonging to the region. Fifty km, or 164,000 feet, is a rather conservative estimate of the distance over which a large power plant may affect air quality. Subsequent studies showed that pollution concentrations from the Meramec plant were still at 1/6 their peak value at this distance from the plant under a typical meteorological condition[2]. Yet it was desired to keep the study area as small as possible to minimize the amount of data required within it and still maintain accuracy. Because of the low population density far from the city, the exact radius of interest is, moreover, for the time period under consideration, of minor importance in calculating aggregate exposure to air pollution.

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(1) A concentration of 1 ppm SO_2 means that by volume, the atmosphere is 1 part per million SO_2 or 2860 $\mu g\ SO_2/m^3$. ([Sulfur Oxides A-7])

The Power Plant Study Region, or PPSR, was defined operationally by first programming the computer to punch the coordinates of points along the circumference of a 50 km circle centered at each power plant, for every 4° of arc. Then the points in the interior region were deleted manually, and the remaining ones arranged in sequence to produce a reasonable straight-line approximation to the PPS Region.

2.2.2 Projected 1970 Population Densities

Rather than reviewing some past situation, I wish to demonstrate the feasibility of load shifting at a time in the near future when it could actually be implemented, 1970. In addition, 1970 promises the operation of the first unit of the Labadie plant now under construction by the Union Electric Company. Thus, in 1970 the St. Louis area should have sufficient generating capacity to make load shifts at most times.

To obtain 1970 population estimates, the county-wide projections of the East West Gateway Coordinating Council were used for the SMSA, Monroe, and Franklin counties. Assuming that each census tract in the SMSA would grow at exactly the rate of its parent county, 1970 populations by tract were calculated for the SMSA. For each surrounding rural county, a single county datum was used. Extrapolating from the projected growth rates of closer counties, a reasonable increase for these outlying counties would be 15% for the period 1960-70. Taking as "data points" or control points the centers of the 344 census tracts (furnished by the Bureau of the Census), plus one (or two for large counties) centrally located points in each of fourteen surrounding counties, a contour map was prepared of 1970 projected population density in the Region(3).

---

[2] Moderate southerly wind, moderately unstable.

This map, Map C-2, was prepared in 2.8 minutes on the IBM 7094 computer using the SYMAP mapping program. Each different symbol of grey represents a different portion of the range of population density. As shown on the table of symbols at the bottom of the map, the levels are of markedly different size. Whereas the lowest represents densities in the range 0 to 500 persons/sq.mi., the highest (black) denotes 20,000 to 70,000 persons/sq.mi. Also below each map are the title and total range of the data values.

Since this paper contains a number of computer maps of this type, it is worth pausing to consider the various symbols. The white lines cutting across the PPSR are the Mississippi

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(3) I am grateful to Mrs. Helen Mansfield for calculating the area of each tract.

River, which here runs generally southeast, and the Missouri River, running northwest. The original maps were at a scale of 25,000 feet = 1" and are reproduced here at 31% of original size. The line of asterisks marks the edge of the St. Louis SMSA. The "P" before the name of each power plant marks its approximate location. The Ashley plant is a few blocks west of the River in St. Louis; Venice and Cahokia are both on the Illinois side.

Several obvious points about the distribution of population emerge from first glance at this map: most of the PPSR is in the lowest level of population density. The highest densities are in the center of St. Louis city, which appears as the large black mass on the west side of the Mississippi River.

Closer examination shows the peaks in density around many of the smaller cities within the region--Alton, on the Mississippi River 20 miles north of St. Louis; East St. Louis, Illinois, across the Mississippi River from St. Louis; and Granite City, slightly north of it, are particularly noticeable. The city of St. Charles, the center on the Missouri River northwest of St. Louis, also shows a local peak in density.

2.2.3 Conversion of Population Densities to a Regular Grid

Now some scheme was needed to compare this map of population density with subsequent maps of air pollution concentrations--i.e., common geographic locations were needed for population and pollution variables. Two possibilities suggested themselves:

(1) Use the census tract and county centers as locations for calculating air pollution concentrations.

(2) Use some arbitrary grid for both pollution concentrations and population density, such as:

(a) Every character location (hence every interpolated value) within the Region on this 1 : 300,000 map. There are about 40,000 such characters in the two-foot square map, each .1" wide by .125" high;

(b) Some rectangular grid of points within the Region.

I eliminated possibility (1) because the census tracts were inappropriately located for calculating air pollution concentration. In downtown St. Louis, two tracts might fall within a single character space at the 1 : 300,000 scale. In rural counties, a data point might represent hundreds of square miles. Possibility (2a) would be impractical. Performing and processing the diffusion calculations for 40,000 points would take hours of computer time; possibility (2b) therefore represented a workable compromise.

First, a 20,000 foot grid was passed over the entire Region, supplemented by a 10,000 foot grid covering most of the cities of St. Louis and Alton--major regions with a population density exceeding 5,000 persons per square mile. To make this grid common to demographic and atmospheric calculations, it was necessary to apportion the population among these initial 1,013 grid cells. In order to do this, a zone was defined for each grid cell, consisting of those character locations in the Region closer to that grid cell than to any other grid cell(4). These zones were defined automatically and stored on a tape by making a "proximal map" of grid cells using the SYMAP program. Grid cells well outside the Region had empty zones, and hence were dropped from further consideration. The remaining grid of 614 points forms the basis of the remainder of this study. The interpolated population density for each character location on the map of the Region was saved on a computer tape. Multiplying these densities times the area of a character cell, and summing over all the cells belonging to any zone yields the total population within an arbitrary zone. As a check on the accuracy of the above conversion of data points, the total population for each zone was divided by the zone area to compute the zone's density.

Map C-3 shows the map of 1970 population density projections based on this grid. Since it displays the same information as Map C-2, the comparison is instructive. The only significant difference is the absence of extremely high densities in downtown St. Louis where the original census tracts were quite small in area. Even though this center portion falls within the 10,000 foot grid, the area over which population density is computed is larger. The very localized high density downtown is averaged with moderately high densities surrounding. Furthermore, the alignment of grid cells was such that the census tracts of highest density were divided among several grid cells. As further checks on this grid, other statistics were calculated--the standard deviation of the densities within each grid zone, and the total population of the Region. The standard deviation within zones ranged between 5% and 15% of the zone's average density--showing that the grid was fine enough so that each cell encompassed reasonably homogeneous population densities(5).

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(4) This was accomplished by the "proximal" type map[14] under SYMAP. The value at each grid cell was the sequence number of that cell. Since the proximal map assigns to each character location the value of the nearest data point, it served to index character cells by grid cell.

From the point of view of the operating model, this treatment of population density and of the PPSR has served to create a grid of 614 data points, giving for each cell the estimated 1970 population residing within the grid zone, and the population density. These will, of course, be needed along with predicted concentrations to compute total exposure.

2.3 PLUME RISE AND SO_2 EMISSION PARAMETERS

The problem of determining the optimal load dispatching, from the point of view of air pollution, requires that the geographic distribution of pollution be computable for any possible load dispatching configuration.

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(5) When integrated from population densities, the total population within the Region overstated the projected 1970 population of the SMSA and surrounding counties. Since densities and relative sizes for each grid zone were reasonable, the source of this overstatement has not been determined. It is possible that an error at this point could bias the damage function to be computed later. Since it is the relative, rather than absolute population density which is of primary interest in a load shifting model, this overstatement would not be critical. The assigned dollar magnitude, but not the shape or relative sizes of the pollution exposure functions, could be in error.

2.3.1 SO_2 Emissions

Although the St. Louis area was the subject of a rather intensive air quality measurement program 1963-65, these empirical data are not adequate to estimate concentrations from a power plant operating at various levels under certain meteorological conditions, for there is no empirical means of determining the share of total observed ground level concentrations of SO_2 for which power plants are responsible.

In place of an empirical examination of supposedly similar past cases, this paper will use a dispersion model to predict concentrations. This means that emission and stack rise parameters are needed for each generating unit, for each possible level of operation. Below I shall discuss the methodology for obtaining these figures.

All the seven power plants shown on Map C-2 except Labadie are now in operation; the latter will begin commercial operation January 1970. The Baldwin plant of Illinois Power is also supposed to begin operation in June, 1970. I have excluded it for lack of information about its fuel cost, stack parameters, emission rates, and because of the uncertain midyear starting date. Since each generating unit or boiler in a plant may be controlled separately, ideally each separate unit should be dispatched separately for maximum efficiency. Since, in fact, there are 26 such units, this kind of treatment would render the problem unduly cumbersome. (Without combining units, the system of equations would have at least 26 simultaneous variables). Therefore, units within a plant were combined wherever they were of similar operating characteristics. For combining, it was required that all units burn exactly the same types of fuels (so no future need for disaggregation would occur), that stack heights and plume rise factors be nearly equal, and that the separate units be relatively small. Large units were purposely kept separate in order to allow the possibility of penetrating the inversion ceiling by generating sufficient power on a single unit. Thus, for example, Sioux units 1 and 2 were not combined, even though they are identical. Table 2-1 and its accompanying notes give preliminary data on each of the 14 dispatching units and the procedure by which it was derived.

Using a short computer program, these data were updated to reflect 1970 gross capacity. Using the ratio of net to gross capacity, 1970, heat inputs, velocities and the stack rise parameter G_1 were corrected to a net heat rate basis. Sulfur dioxide emissions (g/sec) were obtained by the following equation:

$$SO_2 = \frac{P \cdot E \cdot S \cdot k_1 \cdot k_2}{H} \qquad (2\text{-}1)$$

where

P = net power output, kw

TABLE 2-1

Initial Stack, Fuel, Heat, and Emission Data for Major Steam-Electric Generating Units

Plant	Unit	Winter Fuel	Heat Content BTU/lb	1968 Gross Power, MW	Heat eff. BTU/kwh	Stack Diam. M	Exit Gas Temp. °K	Approx.[d] 10^9BTU/hr	Exit Gas[e] Vel. m/sec	Stack Ht. M	Sulfur Content	SO_2 Emission Rate	G_2 [g]	G_1 [h]
Sioux[a]	1	Coal	12000	525	9500	5.73	413	4.990	25.6	183	3.25	3210	1.800	147.0
	2	Coal	12000	525	9500	5.73	413	4.990	25.6	183	3.25	3210	1.800	147.0
Cahokia	1	Oil	151654[i]	80	17806	5.82	464	1.424	7.97	100	2.0	418	2.268	46.4
	2	Oil	151654[i]	35	17806	5.82	464	.623	3.49	100	2.0	183	2.268	20.3
	3	Oil	151654[i]	35	17806	5.82	464	.623	3.49	100	2.0	183	2.268	20.3
	4	Oil	151654[i]	45	17806	5.82	464	.801	4.49	100	2.0	235	2.268	26.1
	1-4	Oil	151654[i]	195	17806	5.82	464	3.511		100	2.0	1019	2.268	33.4
	5	Coal	11740	67.5	17806	5.82	464	1.202	6.73	100	3.0	728	2.268	39.1
	6	Coal	11740	67.5	17806	5.82	464	1.202	66.73	100	3.0	728	2.268	39.1
	5-6	**Coal**	11740	135	17806	5.82	464	2.404		100	3.0	1456	2.268	39.1
Venice[a] (blr)	1	Coal	11350[e]	50	12000	2.90	450	.600	13.14	72	2.43	304	1.074	38.0
	2	Coal	11350[e]	50	12000	2.90	450	.600	13.14	72	2.43	304	1.074	38.0
	3	Coal	11350[e]	53.25	12000	2.90	450	.639	13.90	72	2.43	324	1.074	40.5
	4	Coal	11350[e]	53.25	12000	2.90	450	.639	13.90	72	2.43	324	1.074	40.5
	5	Coal	11350[e]	53.25	12000	2.90	450	.639	13.90	72	2.43	324	1.074	40.5
	6	Coal	11350[e]	53.25	12000	2.90	450	.639	13.90	72	2.43	324	1.074	40.5
(units)	1-4	Coal	11350[e]	313	12000	2.90	450	3.756		72	2.43	1904	1.074	38.6
	5	Coal	11350[e]	106.5	12000	4.11	450	1.275	27.80	72	2.43	649	1.527	57.0
	6	Coal	11350[e]	106.5	12000	4.11	450	1.275	27.80	72	2.43	649	1.527	57.0

(units)	5-6	Coal	11350[e]	213	12000	4.11	450	2.550		72	2.43	1298	1.527	57.0
Meramec[a]	1	Coal	12485	142	10329	3.20	436	1.467	25.48	77	3.00	794	1.123	81.5
	2	Coal	12485	1142	10329	3.20	436	1.467	25.48	77	3.00	794	1.123	81.5
	1-2	Coal	12485	284	10329	3.20	436	2.934		77	3.00	1588	1.123	81.5
	3	Coal	12485	294	9743	4.21	436	2.864	27.99	107	3.00	1638	1.1497	119.4
	4	Coal	12485	350	9743	4.72	436	3.410	27.20	107	3.00	1940	1.1658	128.1
Ashley[a]	2	Coal	12000[e]	19.75	20600[f]	3.96	466	.407	4.94	69	1.0	80	1.556	19.5
	3	Coal	12000[e]	19.75	20600	3.96	466	.407	4.94	69	1.0	80	1.556	19.5
	5	Coal	12000[e]	19.75	20600	3.05	466	.407	8.33	69	1.0	80	1.197	25.4
	6	Coal	12000[e]	19.75	20600	3.05	466	.407	8.33	69	1.0	80	1.197	25.4
	2,3,5,6	Coal	12000[e]	79	20600	3.50	466	1.628		69	1.0	321	1.377	22.5
Wood R[b]	1-3	Coal	11113[e]	464	9850[f]	4.78	436	4.570	35.64	77	3.0	2930	1.676	170.2
	4	Coal	11113[e]	102	9850[f]	5.18	422	1.005	6.44	77	3.0	644	1.7067	145.2
	5	Coal	11113[e]	396	9850	4.57	417	3.901	31.75	107	3.0	2500	1.469	145.2
Labadie[a]		Coal	12000	630	9400	6.25	418	5.92	28.90	214	3.0	3505	2.018	171.9

NOTES:
(Labels on plant names apply to all columns except as noted.)

[a] Taken from memoranda, reports, or site drawings ings [43], or from private communication [29].

[b] Wood River data from personal communication [36].

[c] Subsequently corrected for changes in heat rate with power load, and power used in generation. Computed here as product of capacity times net heat rate.

[d] Computed in proportion to value for Sioux plant, using stack diameter, exit gas temperature, and heat input, for all plants except Sioux and Labadie.

[e] From [48], pp. 9-12, 21-22.

[f] Computed by dividing annual net kwh by total annual fuel burned, as reported in [48].

[g] G_2 = velocity x diameter, m^2/sec.

[h]

$$G_1 = \frac{T_s - T_a}{T_s} \cdot d, \text{ m}$$

[i] Heat content in BTU/gal.

E = net heat efficiency, BTU/net kwh

S = % sulfur content of coal by weight (dry)/100

H = heat content of coal, BTU/lb

k_1 = the constant (454 g/lb) x (3600 sec/hr) x ($\frac{2.00 \text{ g } SO_2}{gS}$)

k_2 = .95, the fraction of SO_2 estimated to be discharged with stack gases(6).

Because plants have increasing incremental (marginal) fuel and maintenance costs as they are loaded near capacity, it is clear that the heat rate cannot be linear. For simplicity, the rate was expressed as a piece-wise linear function. For each plant, two constants were calculated:

$$a = \frac{\text{Average cost at 10\% gross capacity}}{\text{Average cost at 85\% gross capacity}} \qquad (2\text{-}2)$$

$$b = \frac{\text{Average cost at 100\% gross capacity}}{\text{Average cost at 85\% gross capacity}} \qquad (2\text{-}3)$$

Figure 2-2 shows how the heat efficiency E is assumed to vary as a function of the ratio of actual to capacity load on a unit, P/P_o, where E_{av} corrected annual average heat efficiency, assumed to be at 85% capacity. Exit gas velocity, the stack rise parameter G_1, and sulfur dioxide emission rate are all proportional to power load times heat efficiency.

2.3.2 Plume Rise Adjustments

A final adjustment to G_1 was made to account for multiple stacks. The TVA study[16] found that when several nearby

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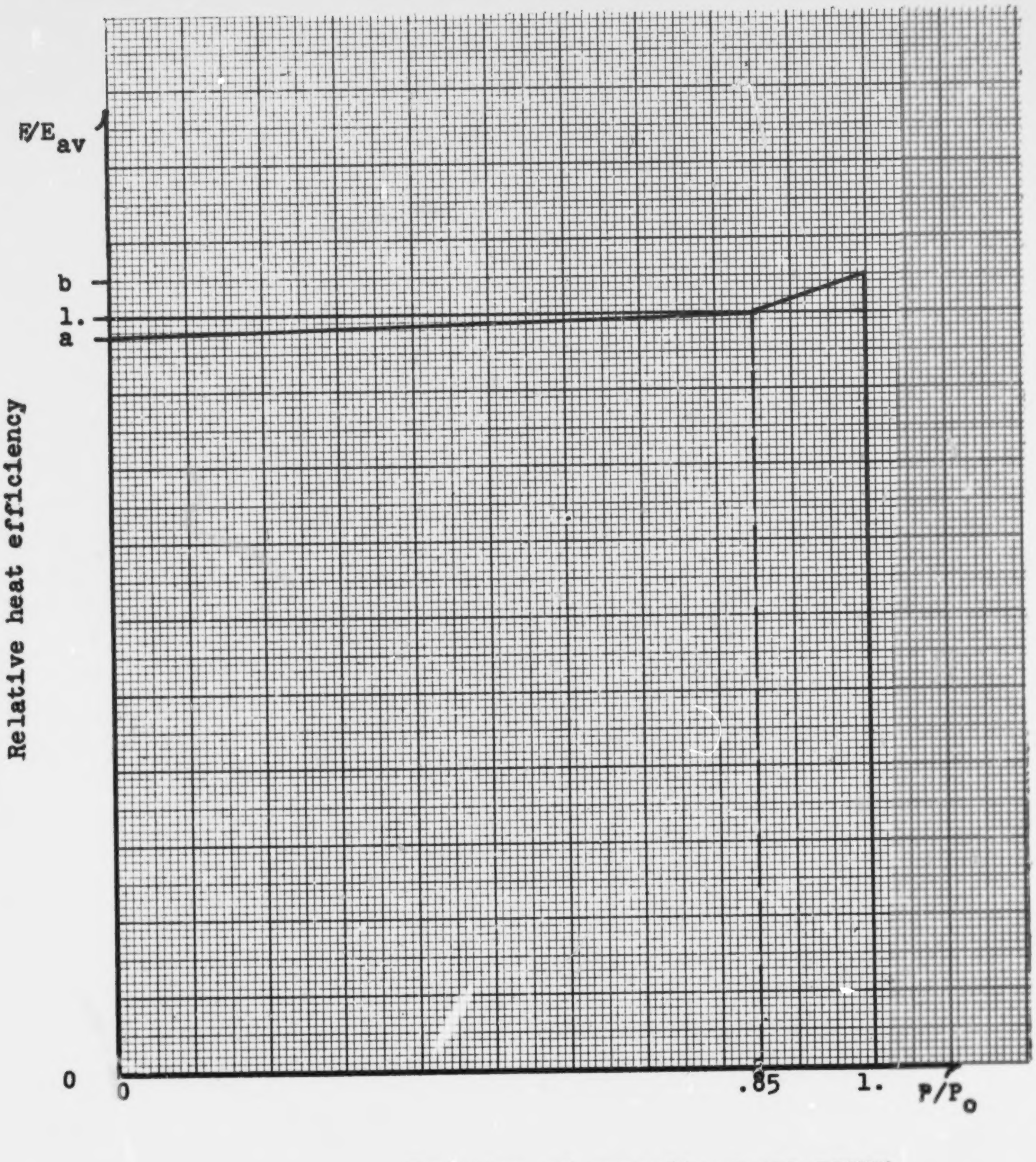
(6) The remainder is absorbed in the ash.

FIGURE 2-2

GRAPH OF RELATIVE HEAT EFFICIENCY AS A FUNCTION OF P/P_o



Fraction of capacity gross power

stacks emit simultaneously, the plume rise is increased by a factor of $(n - 1).05 \cos \theta$, where θ is the angle of the plume axis with the wind axis, and n is the number of stacks in line.

Since the various stacks in line might correspond to different loads and therefore have different G_1's, the following modification was made. The plume rise factor for stack i, considering the multiple stack effect, is:

$$G'_{1,i} = G_{1,i} (1 + .05n \cos \theta) + G_{1,other} (.05m \cos \theta) \cdot k_3 \tag{2-4}$$

where

n = number of additional in-line stacks dispatched jointly with stack i

m = number of in-line stacks dispatched separately from stack i

$G_{1,other}$ = stack rise parameter of separately dispatched units

k_3 = .70, the assumed fraction of total capacity on separately dispatched stacks, given the operation of stack i.

Since the orientation of plants with respect to wind was not known in most cases, and since many plants do not have all stacks in a single line, an exact value of θ could not be used, and an intermediate value of $\theta = 45°$ was inserted. (By definition, $0 \leq \theta \leq 90°$). Although these modifications may be more elaborate than empirical studies justify, the stack rise parameters can be of critical importance in estimating breakthrough of the inversion ceiling.

Based on all the foregoing considerations, values of G_1 and SO_2 emission rate were tabulated for each unit for ten levels of load, from 10% to 100% capacity. In Table 2-2, below, the values corresponding to 100% capacity are given along with other summary information.

2.4 ADAPTATION OF A DISPERSION MODEL

2.4.1 The Gaussian Diffusion Equation

As mentioned in the preceding section, a theoretical dispersion model is mandatory in order to compute estimated ground level concentrations and exposure from operating power plants in various patterns. Though much research has been done in this area in the past decades, dispersal of pollutants in an urban area is incredibly complex. One meteorologist commented that accuracy within a factor of 3 was the best now to be expected[19].

For this study I have adapted the recently-prepared Martin-Tikvart diffusion model for diffusion from tall stacks[25]. The basic concept behind this, and most dispersion models, is that the Brownian motion and turbulence of the atmosphere makes aerosols and gases disperse as if on a random walk from their effective point of emission(7). This diffusion occurs relative to the surrounding air which is of course moving relative to the ground. Furthermore, the atmosphere is a bounded space--bounded by the ground below, and often by an inversion ceiling above. Though some aerosols and gases are deposited on

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(7) A point directly above the source's location at the altitude where the plume becomes essentially level.

TABLE 2-2

COORDINATES, FINAL EMISSION RATES, CAPACITIES, PLUME RISE PARAMETERS, AND RATIO OF NET TO GROSS CAPACITY, ST. LOUIS AREA DISPATCHING UNITS, 1970.

number	plant	units	fuel	location in Illinois coordinates, feet x 1000 vert	hor	Gross power 1970, mw	stack height, m	G_1 m^2/sec	G_2 m	SO_2 emission rate g/sec	Heat_1	Heat_2	n	m	G_1 for separate stacks, m^2/sec	net capacity / gross capacity
1	SIOUX	1	COAL	531.	819.	462.	183.0	157.2	1.80	3327.	0.013	0.067	0.	1.	142.8	0.960
2	SIOUX	2	COAL	531.	819.	462.	183.0	157.2	1.80	3327.	0.013	0.067	0.	1.	142.8	0.960
3	CAHOK	1-4	OIL	197.	705.	495.	100.0	40.7	2.27	1026.	0.024	0.044	3.	2.	37.7	0.954
4	CAHOK	5-6	COAL	138.	705.	495.	100.0	44.7	2.27	1556.	0.059	0.101	1.	1.	32.4	0.949
5	VENICE	1-4	COAL	313.	727.	496.	71.7	49.3	1.07	1843.	0.053	0.041	5.	2.	53.0	0.930
6	VENICE	5-6	COAL	213.	727.	496.	71.7	63.9	1.53	1237.	0.043	0.041	1.	6.	35.3	0.915
7	MER	1-2	COAL	284.	632.	452.	76.4	84.3	1.12	1572.	0.006	0.041	1.	0.	0.0	0.951
8	MER	3	COAL	293.	632.	452.	106.9	119.9	1.50	1590.	0.050	0.030	0.	1.	120.7	0.945
9	MER	4	COAL	355.	632.	452.	106.9	135.3	1.66	1989.	0.034	0.046	0.	1.	117.0	0.966
10	ASHLEY	2-6	COAL	60.	717.	496.	68.7	17.8	1.38	225.	0.049	0.008	3.	0.	0.0	0.917
11	WOOD R	1-3	COAL	471.	800.	509.	76.4	182.7	1.68	3005.	0.029	0.053	0.	2.	119.8	0.960
12	WOOD R	4	COAL	104.	800.	509.	76.4	46.6	1.71	695.	0.020	0.100	0.	2.	156.9	0.962
13	WOOD R	5	COAL	396.	800.	509.	106.9	152.1	1.47	2442.	0.010	0.018	0.	2.	151.6	0.960
14	LABADIE		COAL	620.	688.	301.	214.0	184.6	2.02	3585.	0.013	0.067	0.	0.	0.0	0.974
15	VENICE	1-4	GAS	313.	727.	496.	71.7	48.9	1.07	0.	0.037	0.032	5.	2.	53.0	0.930
16	MER	1-2	GAS	284.	632.	452.	76.4	84.2	1.12	0.	0.010	0.040	1.	0.	0.0	0.951
17	MER	3	GAS	293.	632.	452.	106.9	119.9	1.50	0.	0.050	0.030	0.	1.	120.7	0.945

contact with the ground or structures or absorbed by other materials, this is a small fraction of the total quantity of pollution in the ambient air. To a good approximation, it may be assumed that the earth's surface acts as a reflector of pollution[42].

This study follows the procedures of Gifford, Pasquill, and Turner, as summarized by Turner[42]. It is common knowledge that a plume of smoke (that is, large, visible particulates) increases in depth and width as it is transported downwind. Smaller, invisible particles (particulates) and gases spread similarly and eventually make contact with the ground. The Gaussian diffusion equation[42] below gives the concentration χ at location (x,y,z) from an effective source at (0,0,H); i.e., H is the elevation of the plume centerline, assuming a wind with velocity u in the +x direction, and emission rate Q:

$$\chi_1(x,y,z) = \frac{Q}{2\pi\sigma_y\sigma_z u} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \left\{\exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right]\right\} \qquad (2\text{-}5)$$

Using ground level as the reference, one would be concerned with concentrations at ground level (Z = 0) from which to calculate exposure. In a model for New York City, Harris[17],[32] suggested using Z = 100 meters to obtain effective ground level concentrations, reasoning that the buildings of about this height, and turbulence due to heating would cause uniform mixing below 100 meters. In the PPSR downtown buildings are roughly 30 meters tall, suburban dwellings about 10 meters. Thus, building heights are minor compared to differences in land elevations (St. Louis city lies about 30 m above the Mississippi River)--an important factor too complex for this model to consider. Setting Z = 0, the equation (2-5) becomes

$$\chi(x,y,0) = \frac{Q}{\pi\sigma_y\sigma_z u} \exp - \frac{1}{2} \left[\left(\frac{y}{\sigma_y}\right)^2 + \left(\frac{H}{\sigma_z}\right)^2 \right] \qquad (2\text{-}6)$$

In these equations, σ_y and σ_z are effective cross-wind and vertical standard deviations. Both are functions of atmospheric turbulence (often expressed as stability class) and of downwind distance x.

To evaluate various diffusion equations, the Tennessee Valley Authority[7] calculated SO_2 expected minimum and maximum (to allow for wind variation) concentrations downwind of its Shawnee steam-electric power plant according to several widely used diffusion equations. Counting each trial for which the observed concentrations fell within the predicted range as a success, the relative success rate of each formula could be determined. The Sutton version of the Gaussian formula (essentially the same as Equation 2-5) scored second with 85% accuracy, behind a specially fit PHS-TVA model. I favored Turner's equations for this model, nevertheless, for the following reasons: the equations require fewer meteorological parameters, all of which must be inferred from stability class; they provide an acceptable means for handling a limited mixing depth; and they are already incorporated into the Martin-Tikvart model, which has successfully predicted seasonal averages of sulfur dioxide concentrations.

2.4.2 Limited Mixing Depth

Equations (2-5) and (2-6) make no reference to mixing depth, and assume that diffusion over an indefinite distance is possible. Since pollution is thought not to be able to cross the inversion ceiling from either side, some modification of (2-6) is necessary. Turner's treatment of a limited mixing depth is to assume uniform vertical mixing at distances $x > 2x_L$, where x_L is the distance such that $\sigma_z = 0.47L$ (or 1/10 of the plume centerline extends above the mixing depth, L), so

$$\chi_2(x,y,0) = \frac{Q}{\sqrt{2\pi}\sigma_y L u} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \text{ for } x > 2x_L \qquad (2\text{-}7)$$

For distances x, $x_L < x < 2x_L$, $\chi_1(x,y,0)$ and $\chi_2(x,y,0)$ are averaged.

2.4.3 Cross-wind Diffusion

The Martin-Tikvart model had modified the treatment of the cross-wind diffusion term in order to give seasonal averages--which were simply averages of concentrations under all possible meteorological conditions, weighted by the relative frequency of each condition. For my short-term model, Turner's original equations were more appropriate, and the model was reprogrammed accordingly. The reprogrammed model still permits the averaging of several closely related conditions such as a S and SSW wind, into a single case. To make the model as realistic as possible, it was desireable to base it only on types of data which would be regularly available. Though wind direction data recorded to the nearest degree are available for St. Louis for much of the Interstate Study period, these data are from sensors on the TV tower slightly north of the city center. Close analysis of direction roses([26],Vol. V,pp. 33-37) shows these measurements to be much affected by the heat island effect, for southerly winds were more frequent at the tower than at Lambert field. If a curvilinear wind field were to be employed, such as in the Travelers Research Model for the State of Connecticut[18], this information would be useful. But to make computations manageable, it was necessary to assume a uniform wind field over the PPSR. Since downtown St. Louis represented a small portion of the area, its climate could not be assumed typical of the Region. More representative data were obtained from Lambert Field airport, situated on an elevated plane 12 miles west of the city. Here wind direction was recorded only to the nearest compass point, however, representing a 22.5° sector. Furthermore, as is standard Weather Bureau practice, each hourly reading represents the average of about 10 minutes. Wind direction may vary considerably within that period or over the rest of the hour. Strictly speaking, the downwind direction specification required by the diffusion model is unknown.

2.4.4 Instantaneous Wind Directions

To solve this dilemma, I constructed a frequency distribution on instantaneous wind direction--the parameter which really controls the transport of pollutants. It is derived from a series of conditional distributions. First, given that the recorded wind direction was ϕ (radians), where ϕ is the center point of one of the sixteen sectors, then the mean value η for the 10 minute period over which the observation occurred must satisfy $|\phi - \eta| \leq a$. Here $a = (22.5°)/2 = .963$ radians. Figure 2-3 shows the frequency distribution f_1 of η given ϕ:

$$f_1\ (\eta|\phi) = \frac{1}{2}\, a, \qquad |\eta - \phi| \leq a \tag{2-8}$$

This is simply a uniform distribution centered on ϕ. Next, given that the predominant direction of the wind was η for part of the hour, then the instantaneous direction θ, satisfies $|\theta - \eta| \leq b$ and has the frequency distribution f_2 (see Figure 2-4) for a given b:

$$f_2\ (\theta|\eta) = \frac{1}{b^2}\ (b - |\theta - \eta|) \tag{2-9}$$

FIGURE 2-3

GRAPH OF PROBABILITY DISTRIBUTION f_1 $(\eta|\phi)$

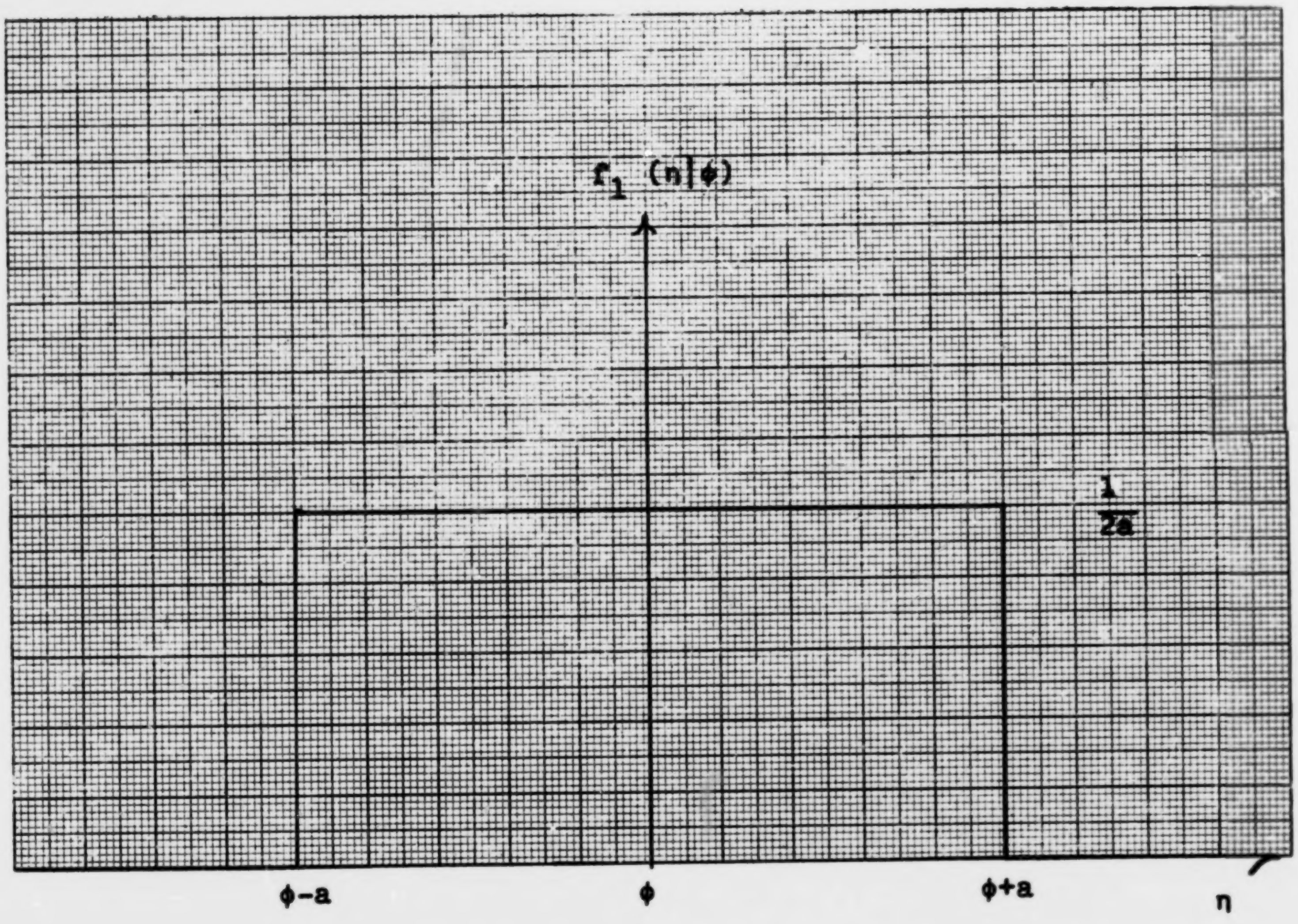
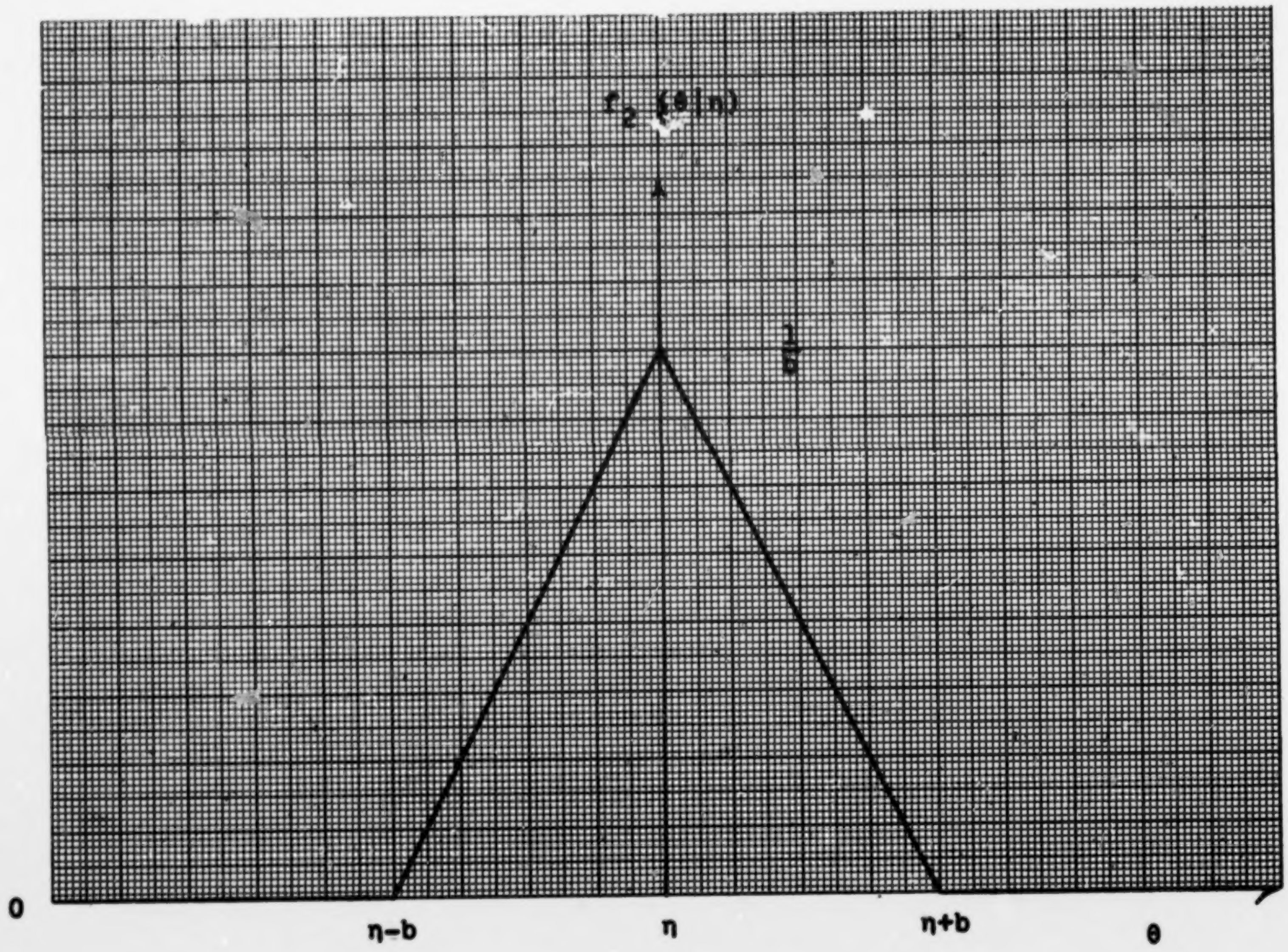


FIGURE 2-4

GRAPH OF PROBABILITY DISTRIBUTION $f_2\ (\theta|\eta)$



The f_2 is a triangular distribution with spread b centered on η, where b is a function of stability class. From analyses of continuously recorded wind direction, the values of b in Table 2-3 may be obtained(8).

Finally, I obtain the frequency distribution f on $\theta|\phi$, the controlling parameter given the recorded statistic η, as follows:

$$f(\theta|\phi) = \int_{\substack{\{\eta\ :\ |\phi - \eta| \leq a \\ \text{and } |\theta - \eta| \leq b\}}} f_2(\theta|\eta) \cdot f_1(\eta|\phi)\,d\eta \qquad (2\text{-}10)$$

Solving yields:

$$f(\theta|\phi) = \left\{ \begin{array}{ll} \frac{1}{2ab}\left[(u + v) - \left(\frac{u^2 + v^2}{2b}\right)\right] & \text{for } r \leq a \\ \frac{1}{2ab^2}\, s\left[t - \frac{s}{2}\right] & \text{for } a < r \leq a + 2b \\ 0 & \text{for } a + 2b < r \end{array} \right\} \qquad (2\text{-}11)$$

where

$$r = |\theta - \phi| \qquad (2\text{-}12)$$

$$u = \min\,(a - r, b)$$

$$v = \min\,(a + r, b)$$

$$t = a + b - r$$

$$s = \min\,(2a, t)$$

---

(8) For these values, as well as for the idea of a frequency distribution on instantaneous wind direction, I am indebted to Assistant Prof. James R. Mahoney of the Harvard School of Public Health.

TABLE 2-3

VARIABILITY OF INSTANTANEOUS WIND DIRECTION BY STABILITY CLASSES

Stability class	b (degrees)	(radians)
Stable	10	.174
Neutral	30	.523
Unstable	45	.785

Figure 2-5 shows the distribution of $\theta|\phi$ for the first case, $b = 10°$. The curve resembles a normal distribution, except that the center is more flattened, and the probability goes to 0 at a finite distance. Nevertheless, it would be a tremendous simplification to approximate this frequency distribution by a normal curve, for it could then be easily combined with other exponential terms in the diffusion equation. To make this approximation, I calculated the variance s^2 of $\theta|\phi$:

$$s^2 = 2 \int_{\{r:\ 0<rsa + 2b\}} r^2 f\ (\phi + r|\phi) dr \tag{2-13}$$

Table 2-4 gives values of s^2 and the standard deviation, s, computed by numerical "integration" using ten rectangles.

By the preceding calculations, I have determined the probability distribution on the precise wind directions to which a plume is subjected over one hour. Variability in wind directions over longer periods depends on general changes in the weather--the passage of a front or movement of a high or low. A particular "case" may be the average of two or three wind directions within the time period. I am concerned with a period of 4-6 hours in this model--a period over which the wind will not shift drastically, and engineers or dispatchers for power plants still have time for decisions. The wind variation term may finally be combined into the cross-wind diffusion s.d. σ_y. It is reasonable to assume the wind variability is distributed independent of cross-wind diffusion, because the former is a

FIGURE 2-5

GRAPH OF PROBABILITY DISTRIBUTION f $(\theta|\phi)$
AND OF NORMAL DISTRIBUTION WITH SAME
VARIANCE, FOR b = (10/11.25)a

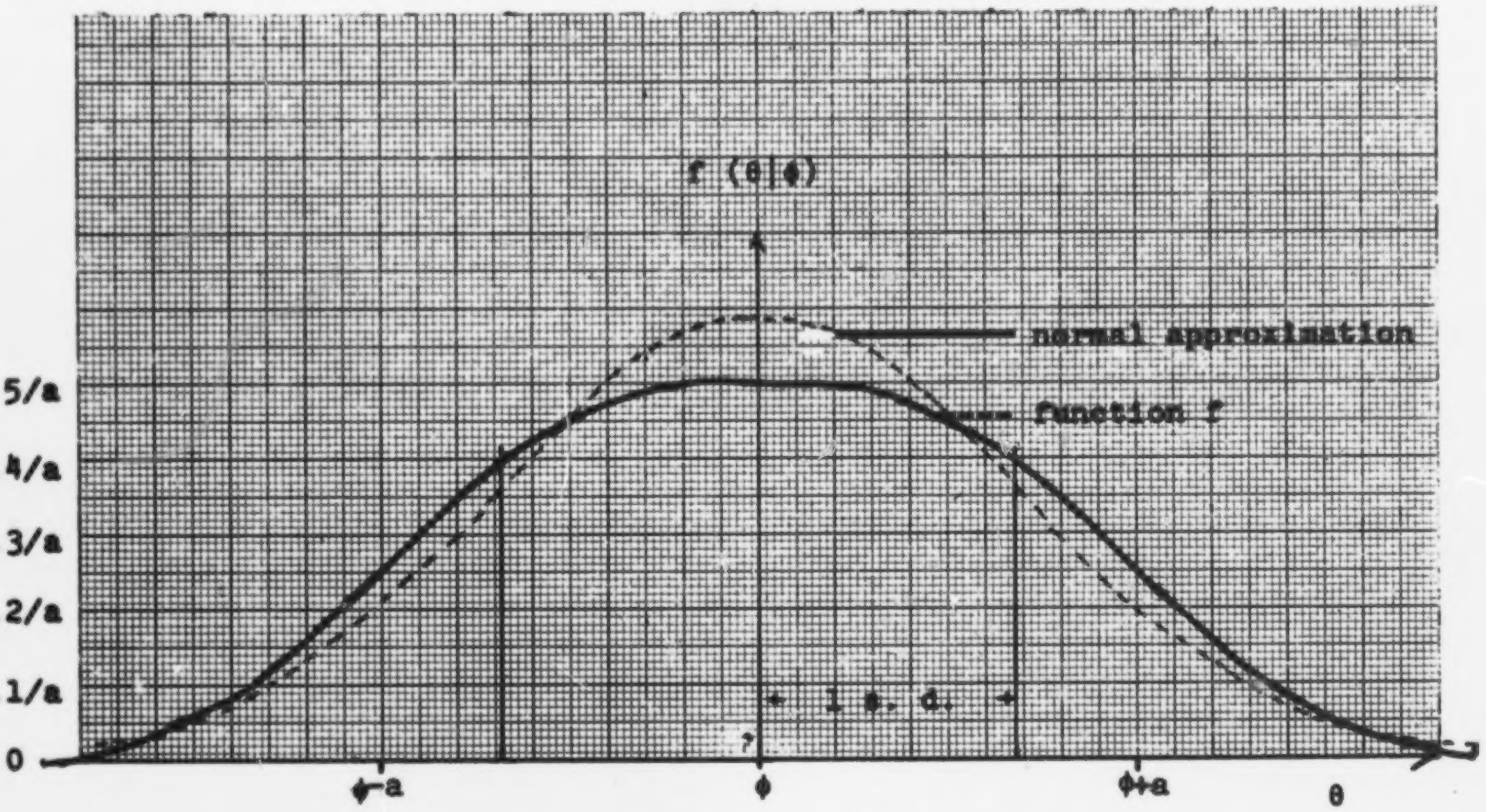


TABLE 2-4

VARIANCE AND STANDARD DEVIATION OF INSTANTANEOUS WIND VARIABILITY ACCORDING TO PARAMETER b

	variance	standard deviation	
b (deg)	s^2 (rad^2)	s (rad)	s (deg)
10	.0179	.134	7.7
30	.0586	.242	13.8
45	.116	.341	19.5

macroscopic phenomenon dependent on major eddies, the latter a microscopic phenomenon connected with small scale turbulence, and random collisions of molecules.

Since both distributions are normal, their variances add. Recall that s^2 is an angular variance, so the cross-wind distance variance due to wind variability at distance x downwind is s^2x^2. Finally, $\sigma_y^2 = \sigma^2_{y,\mathrm{diff}} + x^2s^2$ for each stability class, where σ_y is the diffusion standard deviation. Cross-wind diffusion functions were obtained from the slopes and intercepts of Turner's graphs([42], p. 8). Coefficients for the function of $\sigma_{y,\mathrm{diff}} = a(x/1000)^b$, are given, where x is in meters, in Table 2-5. Alternatively, Pooler's parameters([27], p. 33) could have been used(9). These are slopes and intercepts from best fit lines for tracer studies conducted in St. Louis 1963-65.

Since the scatter in Pooler's data about his best lines is considerable, his lines are not as different from Turner's as would first appear. Furthermore, almost all of Pooler's observations are under 10 km, whereas values at downwind distances up to 100 km are needed in the diffusion model. Because of lower exponents b, the Pooler formulas would predict higher, more localized concentrations at large distances downwind.

In inserting this treatment of cross-wind direction variability, I have dropped the negative exponential function

---

(9) Volume II of his report was received after computations with the diffusion model had been completed, and time did not permit their repetition.

TABLE 2-5

CROSS-WIND DIFFUSION PARAMETERS

	Turner[42]		Pooler[27]	
Stability class	a (m.)	b	a (m.)	b
A - very unstable	215	.826	-	-
B - mod. unstable	155	.826	225	.72
C - slightly unstable	105	.826	185	.72
D - neutral	69	.826	120	.72
E - unstable	50	.826	85	.65

of travel time from the Martin-Tikvart diffusion model, which applied to all point sources. It seemed unsatisfactory for the stated purpose of compensating for wind direction variability, for it violated the conservation of mass law. Some diffusion models have used a "half-life" for SO_2, making the concentration decline exponentially with travel time[18]. The decline in SO_2, however, is primarily its catalytic oxidation to SO_3 and thence to dilute sulfuric acid. Since the purpose of this diffusion model is not basically to compare theoretical and observed concentrations, but rather to compute population exposure, this reaction is unimportant. In fact, however, exposure of persons and materials to sulfate may be even more harmful than an equivalent dosage of sulfur dioxide[41].

2.4.5 Vertical Diffusion

Both $\sigma_{y,diff}$ and σ_z (vertical diffusion s.d.) are functions of downwind distance determined empirically through diffusion tracer experiments. They are generally approximated by linear plots on log-log paper. In this study, the equations for σ_z incorporated in the Martin-Tikvart model were retained. They are of the form $\sigma_z = ax^b + c$ for point sources, with constants as follows in Table 2-6 (x is in meters).

2.4.6 Wind Speeds at Plume Height

Having established cross-wind and vertical diffusion terms, I now must establish wind speed at the plume. Geostrophic (large scale) winds are of lower velocity near the ground due to friction with the earth's surface. This study

TABLE 2-6

PARAMETERS FOR VERTICAL DIFFUSION FROM MARTIN-TIKVART MODEL

Stability class		a	b	c
1 - very unstable		.001	1.89	9.6
2 - moderately unstable		.0476	1.11	2.0
3 - slightly unstable		.119	.915	0.0
4 - neutral	x > 1000 m	2.61	.450	-25.5
	x < 1000 m	.187	.755	-1.4
5 - stable	x > 1000 m	2.61	.450	-25.5
	x < 1000 m	.1343	.745	-1.1

treats the transport of pollutants from their effective origin some distance above the stack top to the ground. Precisely speaking, the wind speed should be incorporated as a continuous function of height, and every concentration evaluated as an integral. Since the estimate of wind velocity as a function of height is somewhat crude, the estimated wind velocity at the stack top was used for each source and assumed to apply at all altitudes. To compute wind speeds aloft, the following formula of Maynard Smith was used([38], p. 55):

$$U_H = U_o\left(\frac{H}{z_o}\right)^{\alpha} \qquad \text{where } \alpha = .50 \text{ stable} \quad = .25 \text{ unstable} \qquad (2\text{-}14)$$

Here U_o is the wind at reference height Z_o,

U_h is wind speed at stack height H.

For use with Lambert Field data, the standard Weather Bureau altitude of 50 feet (15.2 m) was used. Pooler fitted similar power laws in the course of his St. Louis dispersion study. Comparison of surface and 1100 foot wind roses for Lambert Field([26], Vol. V, pp. 5-8) shows that Lambert Field, probably because of its particularly elevated and exposed location, does not seem to obey this law: surface and elevated winds are of about the same average speed. Wind speeds at two levels of the KMOX-TV tower do seem to obey this law, however. If the estimated wind speed is greater than actual, then calculated stack rise and calculated ground level concentrations will be overstated.

2.4.7 Effective Stack Height

A further consideration in the diffusion model is effective stack height. Any observer of a plume of smoke from a large source, such as a power plant, has noticed how the hot gases continue to rise for some time as they are carried by the wind. The elevation H in the earlier diffusion equations is the height of the plume centerline when it becomes horizontal, the stack height augmented by the plume rise--$H = H_{stack} + \Delta H$. Plume rise is of critical importance because of the effect of the inversion layer. Although it acts as a lid on air pollution trapped beneath it, it functions also as a protective barrier on air pollution above it. So long as the inversion ceiling remains below the trapped gas, it cannot diffuse downward to the ground. Sulfur dioxide will remain in the atmosphere until it has been washed from the atmosphere by rain. A secondary effect of stack height is the higher a pollutant is emitted, the more it will disperse before it reaches ground level. Thus high stacks are used on power plants and other large sources because they prevent ground level concentrations from becoming too high, by allowing the pollutant to disperse widely.

Plumes rise for two reasons: (1) the exhaust gas is hot (250°F to 300°F) and so has natural buoyancy compared to the surrounding atmosphere, and (2) the gas has considerable velocity--often as much as 25 m/sec (or 50 mph), imparting considerable momentum to the gas. Winds tend to dilute the plume and dissipate its heat before it has risen much. Plume rise equations are largely empirical, being based on photographs and aerial samples of large plumes; they are subject to errors of up to 100 meters.

This study uses an equation by Holland (reported as equation 4.1, p. 31[42]):

$$\Delta H = \frac{V_s d}{U_h} \left[1.5 + 2.68 \times 10^{-3} p \left(\frac{T_s - T_a}{T_s} \right) d \quad \times k \right] \qquad (2\text{-}15)$$

where

V_s = stack gas exit velocity, m/sec
d = inside stack diameter, m
U_h = wind speed, m/sec
p = atmospheric pressure, 1010 mb
T_s = stack gas temperature, °K
T_a = ambient air temperature, °K
k = 1.4 - 0.1 x stability class number; (1 = very unstable, 4 = neutral, 5 = stable)

or

$$\Delta H = \frac{G_1}{U_h} \quad 1.5 + 2.70\, G_2 \quad \times k \qquad (2\text{-}16)$$

where

$$G_1 = V_s \cdot d \qquad (2\text{-}17)$$

$$G_2 = \left(\frac{T_s - T_a}{T_s} \right) d \qquad (2\text{-}18)$$

Despite the fact that this formula is rated only second out of several plume rise formulas considered in the TVA report, the report did praise its "generally good agreement"[7]. It is by far the simplest formula--its variables are easily expressed in terms of data furnished by the utilities or extrapolated from other plants. Finally, the formula's bias is to understate, so the model will tend to err on the side of caution, overstating the pollution for any case. Although a later chapter will discuss the data for each power plant in the St. Louis PPSR, it should be noted that rather good estimates may be obtained for all parameters except wind speed. This, as discussed previously, is most crudely approximated by a power law. Better wind data aloft, perhaps obtained by balloons, would be critical in trying to implement this study with reasonable accuracy on a daily basis.

Before closing this section, I must discuss the treatment mixing depth. Like temperature, wind direction, or other meteorological variables, mixing depth will vary considerably from day to day, and vary somewhat within the 6-hour period at which this model looks. A uniform frequency distribution was used, bracketing the specified mixing depth by ± 100 m(10). The cumulative probability that the mixing depth is greater than a height, H, given a mean value of L_o in meters, is:

---

(10) A more elaborate triangular fitting was suggested by Assistant Professor James R. Mahoney.

$$f(H) \begin{cases} = 1 & \text{if} \quad H < L_o - 100 \\ = \dfrac{100 + L_o - H}{2 \cdot 100} & \text{if } L_o - 100 \leq H \leq L_o + 100 \\ = 0 & \text{if } L_o + 100 < H \end{cases} \quad (2\text{-}19)$$

This probability distribution merits several interpretations: 1) Out of many periods with mean mixing depth L_o at a particular location, f(H) is the expected fraction for which the actual mixing depth exceeds H. 2) The measurement L_o was taken at some remote location (such as a Weather Bureau Station with pilot balloons) and f(H) represents the distribution on actual values at various locations within the St. Louis area. 3) The actual inversion lid has significant thickness and shifts somewhat during the period. A plume whose centerline falls between the top and bottom of the inversion layer will be carried partly up and partly down. 4) Stack rise parameters fluctuate by ± 100 m about mean. Regardless of the interpretation, f(H) may be considered the actual or expected fraction of an emission at effective height H which will eventually reach ground, given an observed mixing depth of L_o. Expected ground level concentrations become $\chi \cdot f(H)$. The Martin-Tikvart model achieves a similar effect by averaging a number of meteorological cases, though for each case it uses a simple step function.

$$f(H) = \begin{cases} 1 \text{ if } H < L_o \\ 0 \text{ if } H \geq L_o \end{cases} \quad (2\text{-}20)$$

The purpose of this dispersion model is to calculate ground level concentrations as a function of source strength, altitude and wind speed. The Guassian equation (2-6) applies for diffusion beneath the inversion ceiling, once the crosswind and vertical diffusion deviations, effective stack height and wind velocity have been computed. For diffusion at large distances downwind, equation (2-7) will be used instead of (2-6); the factor f(H) in equation (2-19) is used to estimate the fraction of total source strength which diffuses towards ground level.

2.5 COST FUNCTIONS

2.5.1 Fuel Cost

Deriving fuel cost functions was one of the simplest stages in the model construction. For its present dispatching needs, the two major St. Louis power companies have each prepared an "incremental" cost schedule. Incremental costs are the marginal costs incurred by generating each additional megawatt on a unit. Varying from about 1.8 to 6.7 mils/kwh, they reflect primarily fuel costs, and secondarily additional maintenance costs incurred at the higher output. Depreciation, personnel costs, management overhead, and distribution costs are all excluded since they are considered independent of the hourly load on any power plant(11). Table 2-7 gives examples

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(11) Incremental cost data were furnished by Union Electric Company as increasing step functions of load, rounded to the nearest tenth of a mil per kwh. Illinois power data were graphs showing incremental costs as a piece-wise-linear function of load. For simplicity and uniformity, these functions were converted to step functions, preserving the average value and output range of each linear segment.

TABLE 2-7

REPRESENTATIVE INCREMENTAL COST SCHEDULES

Gross Power, mw	Incremental Cost, mils/kwh
Meramec, Unit 4[43]	
0-170	1.9
170-220	2.0
220-270	2.05
270-325	2.2
325-355[a]	5.0
Wood River, Unit 5 [36]	
0-265	1.77
265-370	1.92
370-396[a]	2.18

Note:

[a] Incremental cost for last step assumed to apply up to maximum 1970 output.

of incremental cost functions(12).

It was straight-forward to integrate these marginal cost curves, assuming an initial operating cost of zero(13), to obtain fuel and maintenance costs for each unit in dollars per hour, at any level of output. For combining fuel cost functions with population exposure functions later, the former were evaluated at the ten equally spaced intervals at which population exposure was calculated.

Figure 2-6 shows the total fuel cost for Meramec unit 4, integrated from the incremental cost data shown in Table 2-7. Note that since the incremental costs are a step-function, the total cost curve is a piecewise linear function, with vertices where the step function was discontinuous. Because the changes in incremental cost are small, the changes in slope in the total cost curve are hard to see on the graph. Note that using linear interpolation between ordinates at the equally spaced points on the capacity axis gives a very good approximation to the precisely integrated function. Because the assumption that marginal cost remains constant over the entire step is inexact, the interpolated curve in Figure 2-6 may better represent fuel costs than the exactly integrated curve.

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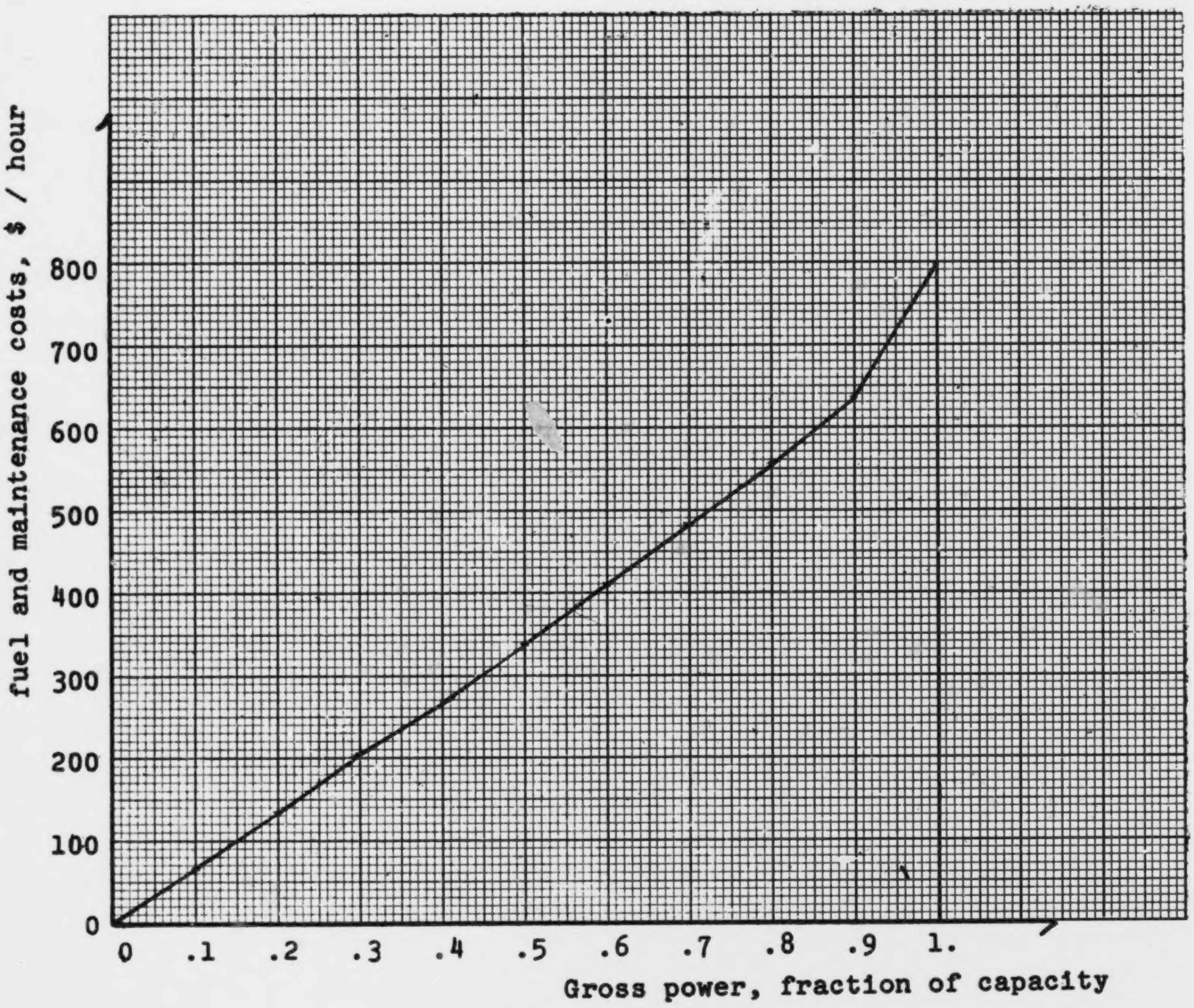
(12) These schedules are private company data, and are not reproduced here in full. Refinements were made in incremental cost values based on their position on the schedule (which listed ranges by increasing incremental cost). If four "steps" all listed the same incremental cost of, say, 2.0 mils/kwh, followed by steps at 2.1 mils, then the last two 2.0 steps were changed to 2.05 mils/kwh.

(13) Though slightly more complex, the problem could have been solved in much the same manner with integer programming with a fixed cost.

FIGURE 2-6

GRAPH OF FUEL AND MAINTENANCE COSTS
FOR MERAMEC UNIT 4, 1970



2.5.2 Sulfur Dioxide Exposure Cost

In the previous chapter a general discussion of some effects associated with air pollution was given. In this section, I undertake the most difficult assignment of trying to assign a dollar order-of-magnitude to sulfur dioxide exposure for a particular distribution (six-hour average) of concentrations over the St. Louis area.

Not only is it beyond the scope of this study to try to establish a function which is exact, but such a goal is still impossible due to gaps in knowledge. Indeed, the author of an entire volume on the economics of air pollution concluded: "But since adequate damage functions are absent, it is impossible to develop cost-of-pollution curves with available data" ([35], p. 153). Since the purpose of this model is to demonstrate the feasibility of an alternate dispatching plan, rather than to implement it on an immediate basis, the purpose will be met by constructing a plausible damage function, and testing the sensitivity of the dispatching model to the penalty function (the cost attached to air pollution). To that end, I shall concentrate on the aspect of air pollution of greatest public interest--health of people exposed to pollution. Since sufficient data do not exist to specify such a function exactly, I shall try instead to obtain an order-of-magnitude estimate by extrapolating from a few careful experiments.

Among the myriad of health effects, one of the most easily measurable and economically assessable effects of air pollution is absenteeism form work due to some diseases believed connected with air pollution, such as respiratory diseases. A study by Dohan (summarized in [2], pp. 9-40 to 9-41) used the personnel and insurance statistics of a large electronics firm to compare the incidence of respiratory disease lasting over 7 days with concentrations of suspended sulfate particulates. With the rough assumption that the sulfate concentration is equivalent to a sulfur dioxide concentration with the corresponding amount of sulfur, then an increase of .0025 ppm SO_2 annual mean concentration is associated with an increase 65/1000 in the incidence of respiratory disease among the female workers sampled. Under further assumptions, based on the annual average SO_2 concentration, the year's total exposure was calculated. An order-of-magnitude figure of 2¢ for the value of lost working time experienced, on the average, when the SO_2 concentration rose by 1 ppm for one hour. A daily wage of $30. multiplied by the incidence of respiratory disease, gives estimated annual loss per year of exposure. Assuming further that loss is proportional to concentration (this is discussed below) and converting to a basis of 1 ppm and one hour gives the rough figure of 2¢.

A similar extrapolation was made from data by Verma[44] on absentee records of a New York insurance firm: Using the simple regression coefficient of 0.15 of average respiratory illness absence rate (per 2000) on twenty-four hour SO_2 concentrations (ppm) again gives a value of about 3¢ as the expected value of lost wages associated with a one-hour exposure to 1 ppm. Making additional allowances for discomfort, for minor illnesses not causing absense from work, the cost of medical treatment, and the possibility of serious complications, the total cost might be as high as 10¢ in total damage person-hour exposure of 1 ppm.

Several notes of caution must be injected here. (1) The damage function assumed here is linear and additive over people, i.e., the exposure of two persons to a certain concentration is of "damage" equivalent to exposing one person to twice the concentration. (2) Furthermore, no threshold concentration has been assumed.

At first these assumptions may seem totally unwarranted. In terms of standard toxicological study, the number of individuals "responding" to various doses of some irritant is often normally distributed.[5] If the dosage were a certain SO_2 concentration for 24 hours and the response, absence from work for one day due to respiratory disease, then the total fraction absent might be distributed like a cumulative normal frequency distribution, which is certainly non-linear. But the measured absence rates were always less than 1%, and few, if any of the estimated 6 hour concentrations due to power plants and other sources would exceed .1 ppm. In this lowest range of the cumulative distribution function, the assumption of a linear damage function is not unfounded. Mathematical simplicity was, of course, another factor. Assuming a damage function non-linear in SO_2 concentration would mean that good estimates of concentrations from other sources would become of large importance for each load - shifting decision, and that the combined "damage" of operating two plants with plumes diffusing over a common area would no longer be the sum of the individual effects of the plants. Not only would a non-linear damage function increase the complexity of the model, it would also make its results difficult to interpret and its sensitivity difficult to analyze.(14) With the assumption of a linear damage function, it is possible to define total exposure, under any distribution of concentrations in "exposure units" or person-ppm-hour, as

$$E = \sum_{i=1}^{614} P_i C_i \tag{2-21}$$

where P_i is the total population and C_i the average concentration in zone i. Aggregating total costs from cost per unit (person) resembles a procedure of Ridker ([47], p. 90).

2.5.3 Combined Cost

After setting a dollar D value for each SO_2 pollution exposure unit, it is possible to construct a combined cost function -- the sum of fuel costs plus pollution exposure costs, expressed in dollars. Thus: combined cost = fuel cost + D x total pollution exposure.

In Figure 2-7, SO_2 exposure is plotted for the same plant, Meramec 4, as Figure 2-6 under case 1 meteorological conditions (See section 4.2.1). Note the extraordinary behavior that pollution exposure actually declines as output increases above 70% of capacity. The decline is caused by a greater fraction of the plume being trapped above the inversion lid (490 meters) at higher output.

Figure 2-8 shows the combined cost, in dollars, using the value D = .10. Note that although the combined cost function does not actually decline, the declining marginal costs (the

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(14) There are "steepest-descent" algorithms for optimizing a non-linear function in many variables, subject to constraints, but they generally require prior knowledge of the convexity of the set of feasible solutions.

FIGURE 2-7

GRAPH OF TOTAL AIR POLLUTION EXPOSURE
FOR MERAMEC UNIT 4, METEOROLOGICAL CASE 1

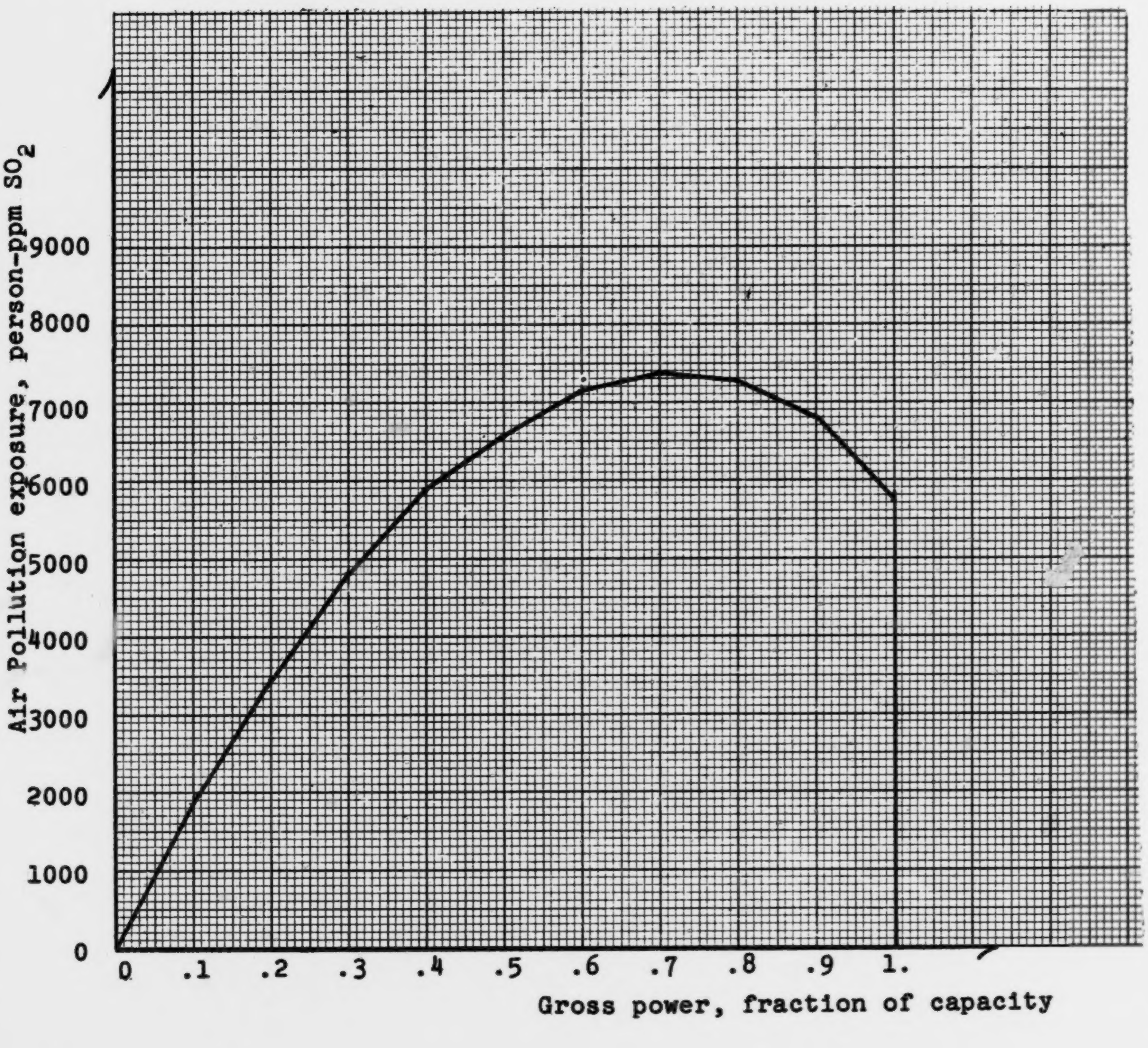
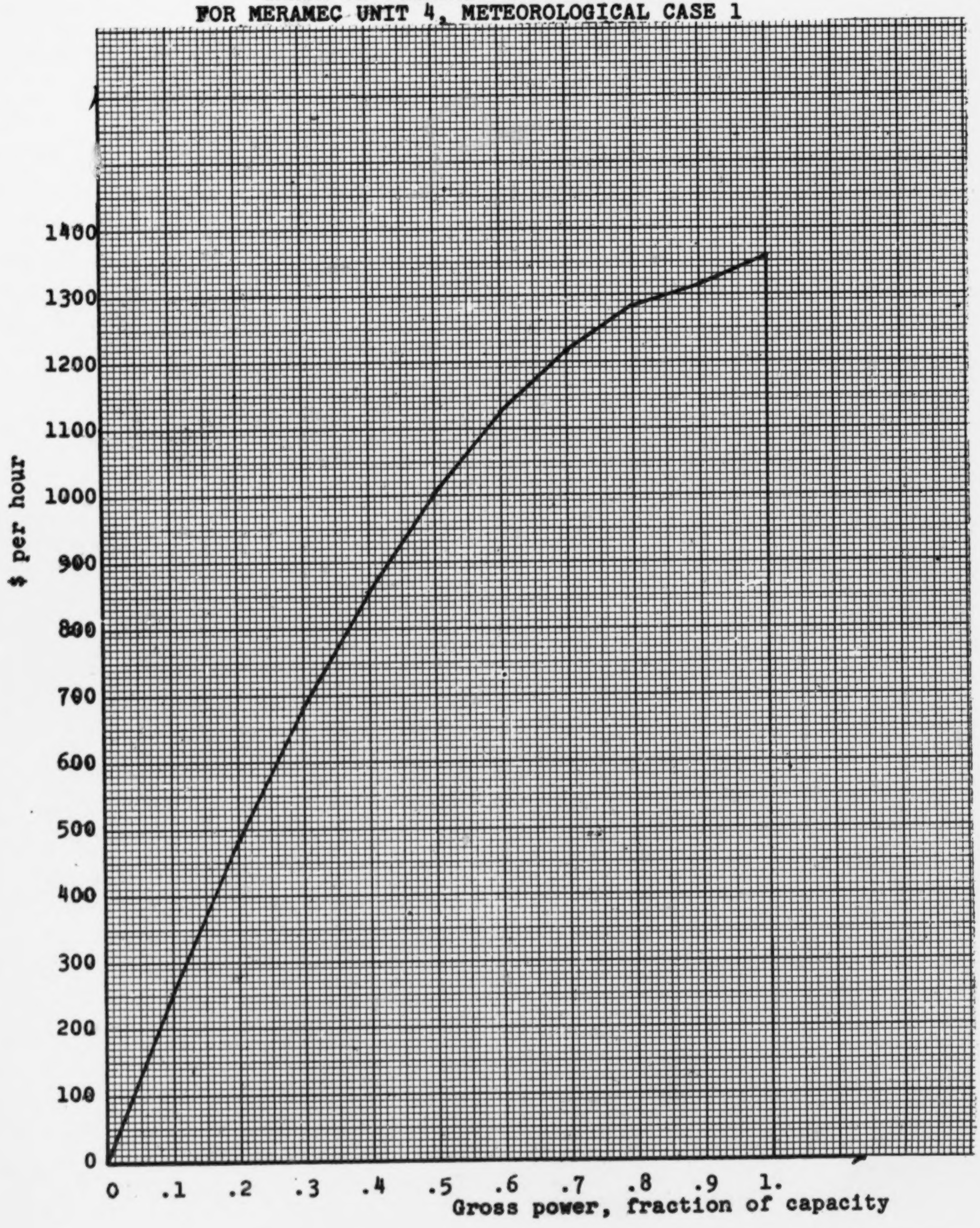


FIGURE 2-8

GRAPH OF COMBINED COST FUNCTION
FOR MERAMEC UNIT 4, METEOROLOGICAL CASE 1



slopes of the linear segments) is marked.

The value of the pollution function may be considered a "penalty cost" -- a penalty the power company should pay the public to compensate it adequately for its exposure to pollution. In Chapter 1, the dilemma of reconciling the desire for clean air with the desire for low-cost electricity was indicated. Now, the dollar value D should represent the number of additional dollars in power generation costs which are acceptable to reduce pollution exposure by 1 unit. In the present situation D = 0 and the system is biased towards low generating cost for electricity, and no concern for SO_2 pollution.

Once this penalty cost or social cost has been included, the electric utility may operate in its previous least-cost fashion, seeking now to minimize total combined costs, subject to power reserve and engineering requirements.

Since these latter requirements are independent from air pollution, it will simplify the problem to remove them, insofar as possible, from the problem.

Although all exposure and cost functions will be specified on an hourly basis, one simplification will be to assume that load shifting would generally be done on a 4 to 6 hour basis. Meteorological data with variability typically observed within this period will be used in the dispersion model, and statistical distribution functions inserted for parameters such as mixing depth and wind direction which vary continuously over the period. The model will then give an average solution for the period, and the problem of warm-up time is avoided. In implementing the solution on an hourly basis, adjustments would be needed for load variations and operating constraints. Because the fixed cost has been taken as zero for all units, the reserve requirement is practically meaningless: if none of the units dispatched under the optimum solution possessed sufficient reserve, then an addition unit could be dispatched, at very low output, solely for reserve. If power demand shifted so that the reserve unit were required, then the system could be resolved for optimal dispatching under combined cost functions at the higher load.

CHAPTER 3

DETERMINATION OF OPTIMUM SOLUTION

3.1 STATEMENT OF THE PROBLEM

I have previously described the derivation of the combined cost curve for each of the fourteen dispatching units. Because of the linear damage function, the cost functions of the units may be treated independently. If $Z_i(P_i)$ represents the cost of generating power P_i from unit i for one hour, then $Z = \sum_{i=1}^{14} Z_i(P_i)$ represents the total cost of generating $P = \sum_{i=1}^{14} P_i$ for one hour. Having incorporated the air pollution damage into the cost functions $Z_i(P_i)$, my problem has become to minimize total cost Z subject to $P \geq P_o$ (i.e., the power demand must be met). Also, since none of these fourteen units are pump-generators, $P_i \geq 0$ for all i must be satisfied. In general, finding a minimum value of a function of 14 variables is a difficult problem. In the present setting where the marginal cost functions $D_{P_i} Z(P_i)$ may not all be monotonic increasing, the problem may be particularly challenging, for the space of feasible solutions $(Z, P_1, \ldots, P_{14})$ with $\Sigma P_i \geq P$ need not be convex. Thus there may be a large number of locally best solutions(1). Standard steepest descent methods may fail to find the globally best solution when many local minima for Z exist.

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(1) That is, they cannot be improved by any infinitesimal change while remaining within the boundary conditions.

First, it is easily established that the space of feasible solutions is not empty. Since a real power system is being modeled, it necessarily has sufficient steam-electric capacity to meet net steam-electric demand(2). Consideration of pollution exposure does not affect constraints or total capacities of units, but only changes the shape of the objective function. Thus, the feasible space is not altered.

3.2 RESTATEMENT OF COST FUNCTIONS

3.2.1 Piecewise Linear Approximation

I do not in fact know the shape of the entire cost function, but only its value at ten equally spaced locations, plus the origin. Although the damage and fuel cost functions are complicated, the principal terms are the quantity of emissions and fuel burned, and the fraction of pollutant trapped beneath the inversion ceiling--all of which are approximately linear functions of power load over a small range. To a good approximation then, the combined cost function may be considered linear between adjacent specified values. The function $Z_1(P_1)$ may now be represented as a piece-wise linear function with ten segments. Before it can be used, the curve must be checked for a possible correction.

3.2.2 Treatment of Declining Absolute Costs

It is possible that not only marginal cost, but also absolute cost, may decline with increasing output. For a large plant with a high stack (such as Meramec unit 4), the plume may be sufficiently strong to pass substantially through the inversion ceiling at full load, and can be trapped under the lid for light loads. If the air pollution penalty cost is large in relation to fuel cost, this marked decrease in air pollution exposure under full load will actually mean a decline in the total combined cost function. In practice one would not operate at a point where he could obtain more output for less input, unless there were a problem of disposing of the excess output. Since a utility could always sell this excess power, the disposal problem does not apply to electricity. Expressed algebraically, this modification becomes step 0: for units with a declining cost curve at point V_i, the curve is modified to represent the cost of producing output of at least V_i. Algebraically, if $\{(V_i, Y_i)\}$ represents the original cost curve, then $\{(V_i, Y_i')\}$ is the modified cost curve, where $Y_i' = \min \{Y_j | i \leq j \leq N\}$.

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(2) Power bought from other utilities and hydroelectric power have been subtracted from total demand to obtain net steam-electric demand.

3.2.3 Reduction in Number of Linear Segments

Closer examination of the modified combined cost functions reveals that the ten segments have superfluous vertices: the slopes of several adjacent segments may be nearly identical, because the incremental fuel cost may vary little or not at all, and the fraction of the pollutant trapped beneath the inversion layer may change at a constant rate. Then, instead of ten segments, many fewer will suffice. Although I have yet to show how the optimization problem may be solved for piecewise linear functions, the reader can anticipate that the greater the number of segments constituting each function, the more complicated the solution.

The following is a simple algorithm for reducing the number of vertices to represent a piecewise linear function.

Step 1: Assume the vertices to be (V_i, Y_i), for $i = 0$ to N, and $(V_0, Y_0) = (0, 0)$. For ten initial segments, I use $N = 10$. Suppose I wish to approximate the functions between vertices i and j by a single segment. For each intermediate segment k, $i \quad k \quad j$, I compute the approximated value

$$Y'_k = (V_k - V_i) \frac{Y_j - Y_i}{V_j - V_i} + Y_i \tag{3-1}$$

and the relative error $\left| \frac{Y'_k - Y_k}{Y_k} \right|$. If this error exceeds some predetermined tolerance (e.g., 2.5%), the approximation is considered unsatisfactory, and substitution of a single segment from vertex i to j rejected. The greatest value of $j \leq N$ for which all the intermediate vertices are satisfactorily approximated marks the endpoint of a segment. Since the simplified function necessarily fits exactly at vertices i and j, with $i < j$, each application of the algorithm must extend the simplified function by at least one segment. As soon as vertex N is reached, the process stops.

Because segments with smaller slope than their predecessor cause the space of feasible solutions not to be convex, the reader might further anticipate that such segments will be a special complication, and therefore a particular effort should be made to reduce the number of such segments as much as possible. Since I shall soon show the reader's anticipation to be well-founded, I shall proceed with the description of step 2 of the simplification algorithm.

Step 2: Use this step only if the following conditions are met:

1) The preceding application of Step 1 extended the simplified function one segment;

2) The slope from vertex $i + 1$ to $i + 2$ (with i defined as in step 1) is less than that from vertex i to $i + 1$ (declining marginal costs), and

3) The slope from $i + 2$ to $i + 3$ is still smaller than that from $i + 1$ to $i + 2$--marginal costs continue to decline. If only step 1 were used it is possible that three segments would be required to extend the "simplified" function from vertex i to $i + 3$, so the function would not have been simplified at all over that particular portion.

With the following procedures, the number of segments between vertices i and $i + 3$ is reduced to two: the lines from i to $i + 1$, and from $i + 2$ to $i + 3$ are extended towards each other until they intersect at some point (V,Y). The slope conditions are such that $V_{i+1} \leq V \leq V_{i+2}$ and $Y_{i+1} \leq Y \leq Y_{i+2}$. This new vertex (V,Y), not the vertex V_{i+1},Y_{i+1}, is the next in simplified linear approximation. The subsequent vertex is (V_{i+3},Y_{i+3}). The effect of reducing the number of segments by one has been to reduce the number of instances of declining marginal costs in the simplified function. The simplified function fits perfectly over $V_i \leq V \leq V_{i+1}$ and $V_{i+2} \leq V \leq V_{i+3}$ and overstates along $V_{i+1} \leq V \leq V_{i+2}$. Figure 3-1 shows the application of the simplification algorithm to the Meramec 4 cost curve of Figure 2-8. Note that N has been reduced from 10 to 3.

The result of steps 1 to 3 is a short sequence of vertices (V_i, Y_i) which completely specify the total combined cost curve of each unit. The vertices have been selected to represent major changes in direction--the curve may be assumed linear in between.

3.2.4 Formulation as Mixed-Integer Programming Problem

To solve this problem, the technique of mixed-integer programming(3) is now appropriate. Markowitz and Manne[24] suggest a procedure whereby 0-1 mixed integer variables may be used as indices in translating a problem with declining marginal costs constraints into a programming problem.

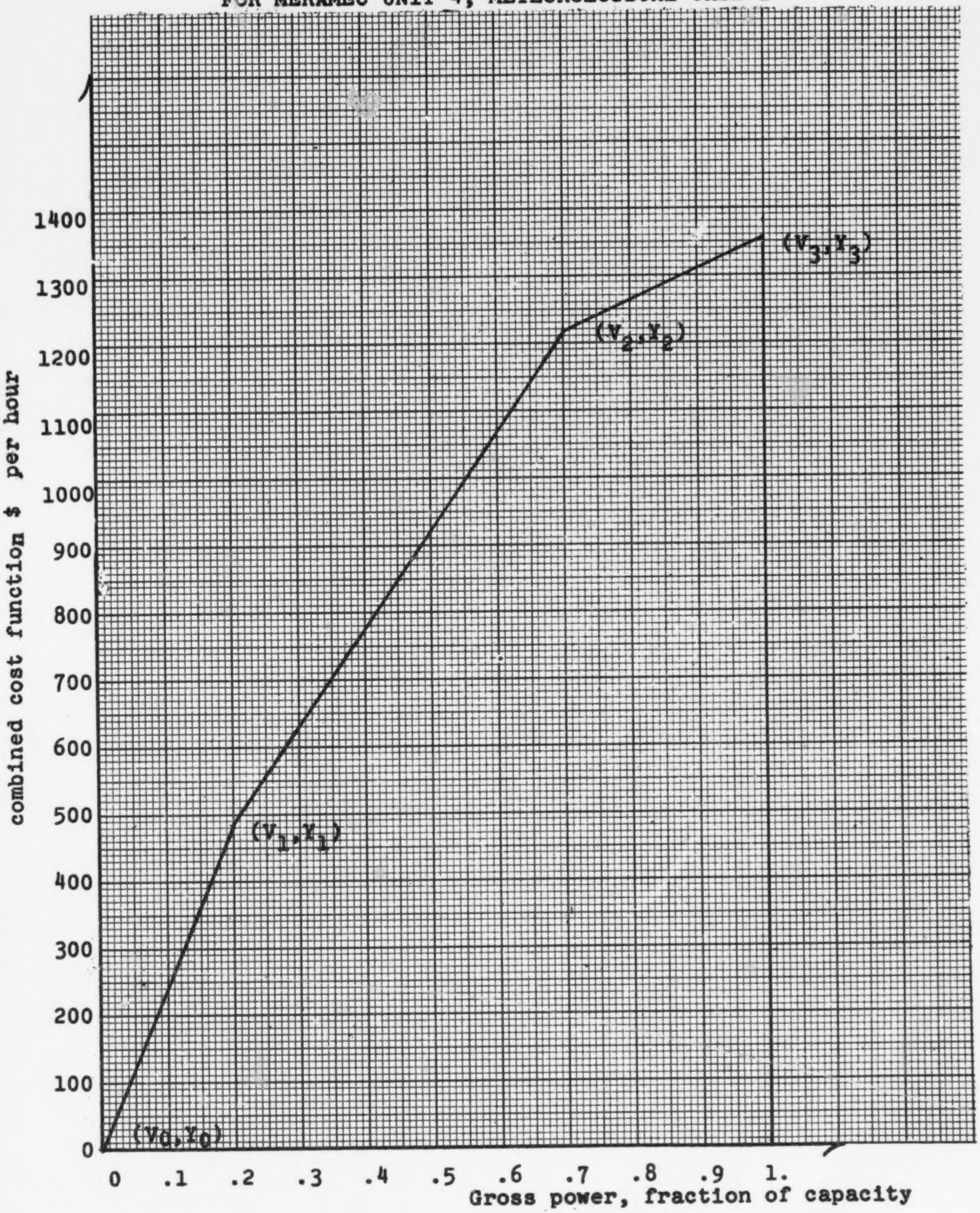
Markowitz's scheme for introducing integer variables, translated into my notation, is as follows. Let (V_i, Y_i) be vertices at which marginal costs decline $(i = 0, \ldots, N)$. Define N integer variables X_i, for $i = 1$ to N, and N continuous variables Q_i.

---

(3) Mixed integer programming is simply linear programming with the added requirement that certain variables be integers.

FIGURE 3-1

GRAPH OF SIMPLIFIED COMBINED COST FUNCTION FOR MERAMEC UNIT 4, METEOROLOGICAL CASE 1



Let

$$X_i \geq \frac{1}{V_i - V_{i-1}} \; Q_i \qquad i = 1,\ldots,N \qquad (3\text{-}2)$$

$$X_i \leq \frac{1}{V_{i-1} - V_{i-2}} \; Q_{i-1} \qquad i = 2,\ldots,N \qquad (3\text{-}3)$$

$$Q = \sum_{i=1}^{N} Q_i \qquad (3\text{-}4)$$

$$Z = \sum_{i=1}^{N} A_i Q_i \qquad (3\text{-}5)$$

$$X_i = 0 \text{ or } 1 \qquad i = 1,\ldots,N \qquad (3\text{-}6)$$

$$Q_i \geq 0 \qquad i = 1,\ldots,N \qquad (3\text{-}7)$$

The purpose of constraints (3-2) and (3-3) is to force all Q_i to the left of segment j to their maximum as soon as $Q_j > 0$. For example, suppose $0 < Q_3 < (V_i - V_{i-1})$. Then by (3-2) and (3-6) $X_3 = 1$, which by (3-3) forces Q_2 to at least $V_2 - V_1$, and by (3-2) and (3-6) to not more than $V_2 - V_1$. Continuing this reasoning requires $X_1 = 1$ and $Q_1 = V_1 - V_o$. Notice, in fact, that X_1 is superfluous and could be replaced by the constant 1. Though Markowitz's constraints work satisfactorily, I will show that they are unnecessarily cumbersome. First though, I shall describe the procedure for efficient numerical solution of a mixed-integer programming problem.

For solving the dispatching problem on the IBM 7094 computer, I will use an algorithm[11] and computer program[12] by Davis, Kendrick, and Weitzman. Using what the authors call a branch and bound algorithm, the computer makes judicious choices on setting the integer variables. Each setting of the integer variables creates an essentially new linear programming problem. A problem with 20 independent 0-1 integer variables could generate as many as one million separate cases to be considered. The program description indicates that the time for solution increases with the number of rows, columns, and matrix entries in the constraint matrix. For a quick solution, as well as for elegance, the linear constraints should be specified with as few rows, columns, and entries as possible. The program MFOR-01-MIP(4) assumes that all variables will be non-negative. Coefficients may be of either sign, and inequalities must be converted to strict equalities through the introduction of non-negative stack variables. Constraints must also be sufficient to guarantee that all the integer variables be less than 1. Direct translation of Markowitz's conditions would mean one constraint and one slack variable for each inequality (3-2), another slack for each inequality (3-3), and a third slack for each type (3-6). Equations (3-4) and (3-5) would add two more constraints, to bring the total to $3N + 1$ constraints with $3N - 1$ slack variables.

---

(4) I am indebted to Assistant Professor David Kendrick for furnishing a copy of the program deck, and to Antonio Poblete for offering suggestions on its use.

3.2.5 An Efficient Constraint Matrix

After some experimentation, I have developed the following improved procedure. The integer variables X_i will be used as indicators so exactly one of them is 1. And only one of the Q_i (the one for which $X_i = 1$) can be non-zero. The revised constraints are as follows:

$$Q_i - V_i X_i + (V_i - V_{i-1})\, S_i = 0; \quad (i = 1,\ldots,N) \qquad (3\text{-}7)$$

$$S_1 + S_2 + \ldots + S_N + S_{N+1} = 1 \qquad (3\text{-}8)$$

$$Q_1 + Q_2 + \ldots + Q_N - Q = 0 \qquad (3\text{-}9)$$

$$X_1 + X_2 + \ldots + X_N = 1 \qquad (3\text{-}10)$$

$$\left[\sum_{i=1}^{N} A_i Q_i + (Y_{i-1} - A_i V_{i-1})\, X_i\right] - Z = 0 \qquad (3\text{-}11)$$

where

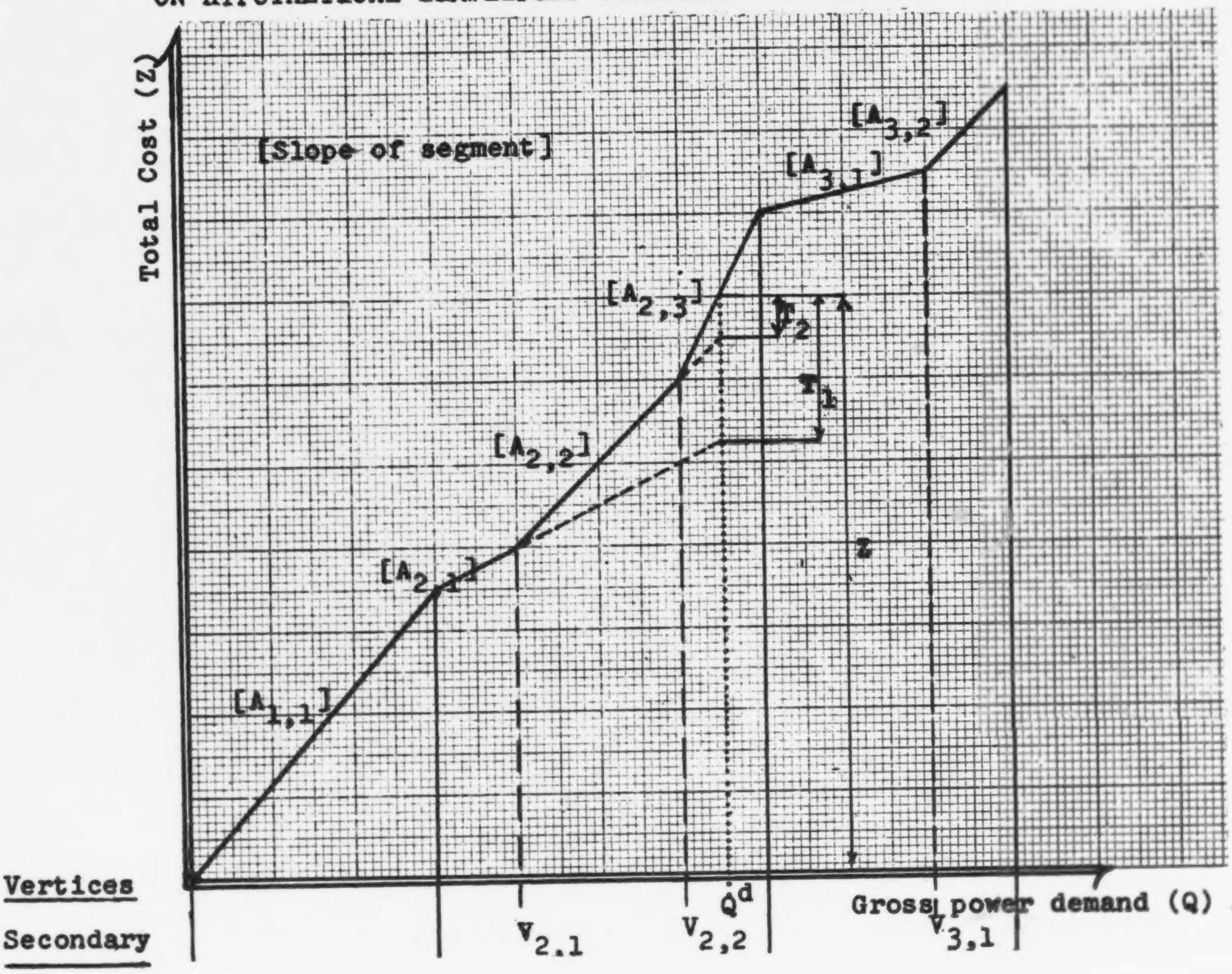
$$A_i = \frac{Y_i - Y_{i-1}}{V_i - V_{i-1}}\,; \quad (i = 1,\ldots,N) \qquad (3\text{-}12)$$

Suppose again the plant is to operate with $V_2 < Q < V_3$. The constraints (3-7) require that some Q_i and the corresponding X_i be positive. By (3-10), only one of the X_i can be positive, hopefully for $i = 3$. First suppose it were $i = 2$. Since Q_2 must equal Q, and $X_2 = 1$, this violates constraint (3-7) for $i = 2$ for $Q_2 - V_2X_2$ is already positive, and the addition of some positive slack variable cannot make it zero. Now suppose the program chose $i = 4$ (it is assumed $N \geq 4$). Then $Q_4 = Q$, $X_4 = 1$ and (3-7) is satisfied for $i = 4$ if $S_4 = \frac{V_4-Q_4}{V_4-V_3}$. But since I began with $Q < V_3$, S_4 is greater than 1, violating constraint (3-8). As desired, (3-8) is satisfied for $i = 3$ by $X_3 = 1$ and $S_3 = \frac{V_3 - Q_3}{V_3 - V_2} < 1$. Inequalities (3-7) for $i \neq 3$ are met by $Q_i = X_i = S_i = 0$. Since all of the Q_i's and X_i's except one pair are 0, (3-11) reduces to $Z = Y_{i-1} + A_i (Q_i - V_{i-1})$ which is clearly a straight line through (V_{i-1}, Y_{i-1}) and (V_i, Y_i). I have now simplified the problem to $N + 4$ constraints with N auxiliary non-negative variables, and one slack variable, S_{N+1}.

I wish to carry this analysis still further, however. Suppose, for generality, that the cost curve is of mixed curvature -- that the primary vertices are the origin and those at which the marginal cost decreases, but that there are secondary vertices at $V_{i,0},\ldots,V_{i,K_i-1}$ between V_{i-1} and V_i with rising marginal cost. First, I define $V_{i,0} \equiv V_{i-1}$, and $V_{i,K_i} \equiv V_i$. Let the $Y_{i,j}$ be the ordinate at $V_{i,j}$ (See Figure 3-2). The normal linear programming problem allows for rising marginal cost, for its objective of minimizing cost means that segments of the cost curve will be used in their natural order. Under the system established, these secondary vertices are handled by substituting equations (3-13) and (3-14) for (3-11) and (3-12):

FIGURE 3-2

PRIMARY AND SECONDARY VERTICES, AND SLACK VARIABLES ON HYPOTHETICAL SIMPLIFIED COMBINED-COST FUNCTION



Primary[a]	$V_{1,0}$	$V_{2,0}$	$V_{3,0}$	-
Primary[b]	-	$V_{1,1}$	$V_{2,3}$	$V_{3,2}$
Primary[c]	V_0	V_1	V_2	V_3

NOTES

[a] Notation as initial vertex of segment

[b] Notation as terminal vertex of segment

[c] Notation as original (single-subscripted) vertex

[d] Values of variables X_1 and Q_1 for this placement of Q are:

$X_1 = 0$ $X_2 = 1$ $X_3 = 0$; $T_3 = 0$

$Q_1 = 0$ $Q_2 = Q$ $Q_3 = 0$

$$\left[\sum_{\{i \,|\, K_i \geq j \text{ and } 1 \leq i \leq N\}} [A_{i,j}Q_i + (Y_{i-1,j} - A_{i,j}V_{i-1,j})\, X_i] \right] + T_j - Z = 0 \qquad (3\text{-}13)$$

$$(j = 1,\ldots,K)$$

where

$$A_{i,j} = \frac{Y_{i,j} - Y_{i,j-1}}{V_{i,j} - V_{i,j-1}} \qquad (3\text{-}14)$$

and

$$K = \max \{K_i \mid 1 \leq i \leq N\} \qquad (3\text{-}15)$$

T_j are slack variables

Considering the constraints (3-13) as a matrix, each column i continues downward for K_i rows, after which terms in Q_i and X_i are deleted. K_i is the number of the last vertex in the segment V_i to V_{i+1}, starting with 0 at V_i and ending at V_{i+1}. There are now K (3-13) inequalities. For any Q_i positive there are now K_i equations putting constraints on the total cost Z. Since the marginal costs are increasing, the final cost Z cannot be below any of the segments in V_{i-1} to V_i. Since Z cannot simultaneously be on all the price lines, the new slack variables T_j have been added. Note the compactness of this mode of expression. A cost curve with as many as N x K vertices, plus the origin, may be characterized by only K + N + 3 constraints.

I have now shown how it is possible to characterize each dispatching unit by a set of linear constraints out of which come two important variables Q and Z for each of the 14 units. The interconnections are simple. The objective is to minimize total combined costs, or minimize $\sum_{m=1}^{14} Z_m$. The final constraint is, of course, that demand must be met. Following the convention of power dispatchers, I will leave Q in terms of gross power for each unit. Yet the important demand is for net power--gross power less the portion used to run motors, fans, and pumps to support generation--or 90% to 97% of gross power of a unit. Denoting the ratio of net to gross power on unit m by B_m, the final constraint becomes

$$\sum_{m=1}^{14} B_m Q_m = \text{Net Power Demand.} \tag{3-16}$$

3.3 ANALYSIS OF MIXED-INTEGER PROGRAMMING

Along with determining a mixed-integer programming solution, the load-shifting model should also contain a procedure for analyzing results. Because the model is complicated and its results difficult to visualize, I shall employ several approaches. Most important will be computer mapping, for it permits rapid and easy graphical display of sulfur dioxide concentrations in the PPSR under various operating schemes. Similarly, contour maps of improved (or of worse) SO_2 concentrations resulting from the use of load shifting may be made on the computer. Maps may also be printed of densities of air pollution exposure to show the combined effect of the distributions of population density and of sulfur dioxide concentrations. To study the detailed behavior of the model and of these two distributions by some other means would be almost impossible--for one would have to keep in mind the concentration and exposure at 614 grid points. For the most interesting solutions, I have prepared maps of each of the above types.

For a non-graphical presentation of results, I have also calculated summary statistics for each solution of the model--the sum over all plants of the values of all pollution exposure functions, cost functions, and combined cost functions. But without a graphical picture, the aggregate value of the air pollution exposure function is a difficult number to interpret, since such an exposure function has not, to my knowledge, previously been used computationally in air pollution literature.

By necessity, the operating costs for fuel and maintenance, as presently computed, will be higher(5) under load shifting than without. For since the traditional dispatching procedure achieved the least cost solution, some alternative solution cannot have still lower cost, where "cost" is still measured as variable operating costs. It is possible that in some larger sense, the optimal dispatching solution will be of lower aggregate cost to the electric utility when probable decreased absentee rates among employees and prolonged life of plant and transmission facilities, under the less corrosive atmosphere, are considered. Since fuel cost is higher under the load-shifting optimal solution, air pollution exposure cost must be lower, or the load-shifting solution would not be optimal.

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(5) It is possible, though unlikely, that cost functions and net demand will be such that no improvement will result from load shifting, so both fuel cost and exposure cost will be the same as before. Even if an improvement does result, there is no *a priori* guarantee of large magnitude.

CHAPTER 4

OPERATING THE LOAD-SHIFTING MODEL

4.1 REASON FOR SOLVING THE MODEL

In Chapter 2, I have described the elements of a load-shifting model to minimize exposure to air pollution. Testing and reviewing each element individually will check that it functions correctly, but gives little indication of how it will interact with other elements in the long model. In order to test the model for a few realistic cases, wind rose data, hourly wind speed and direction from Lambert field airport, and hourly stability class estimates were scanned for Fall and Winter 1964-65, and a realistic meteorlogical condition constructed around each of the two most frequent wind directions -- South and West-Northwest ([34], p.22).

4.2 CASE 1 - MODERATE SOUTHERLY WIND

4.2.1 REQUIRED DATA

Case 1 represents a meteorological case with a moderate southerly wind. The values of the meteorlogical parameters under Case 1, and the periods from the weather records on which this case is based, are shown in Table 4-1. The mixing depths for each stability class are the expected values calculated by the Martin-Tikvart model for the stability class, based on the mean maximum mixing depth for late Fall and Winter of 490 meters. For Case 1 the diffusion model had to average six different dispersion conditions to use each combina-

TABLE 4-1

CASE 1 - MODERATE SOUTHERLY WIND

DISTRIBUTION OF METEOROLOGICAL PARAMETERS

Stability	Number[41]	Frequency	Mixing Depth, m.
Neutral	4(a)	.3	490
	4(b)	.2	295
Stable	5	.5	100
		1.0	

Wind Direction	Frequency
South	0.5
South-south-west	.5
	1.0

Surface Wind Speed[a]

4.9 m/sec

Representative Periods

Feb. 5, 1965	6 a.m. - 10 a.m.
Nov. 9, 1964	5 a.m. - 9 a.m.

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[a] Measured at 15.2 m above surface

tion of stability class, mixing depth, and wind direction. Variation in wind speed was excluded because it was thought to be a minor factor, and would have tripled the amount of computation in using each case for the diffusion model. To use the diffusion model four pieces of information were brought together: meteorological parameters, such as Case 1, emission parameters from Table 2-2, and the coordinate locations of each grid cell and the estimated population of the surrounding zone.

The result was a compilation of concentrations expected from each dispatching unit at each of the ten different levels of output, from 10% to 100% of capacity, plus zero output. For each unit, the computer also calculated the density of pollution exposure within the PPSR at each level of output, and the total population exposure expected. To include another element into the model, it was recognized that not all units were really available up to their capacity output throughout the year. Typically several units will have restricted output or even be entirely unavailable due to "outages" -- repairs, modifications or routine maintenance -- an any given day. From inspection of the schedule of planned outages for the Union Electric Company and unplanned outages indicated in the dispatching record, the following restrictions were arbitrarily created to resemble the typical reduction in available power due to outages in late Fall or Winter:

Unit	Normal Capacity, mw	Restricted Capacity, mw
Sioux unit 1	531	250
Meramec unit 3	293	150

4.2.2 Cost Functions and Load

The results of Case 1 were rather dramatic. Because of the low mixing depth accompanying the stable atmosphere iteration in the diffusion model, it was fairly easy for most plumes to penetrate the inversion lid. For the stable atmosphere calculation, the effective stack height of the Sioux unit 2 varied from 195 m to 293 m. at full capacity. Thus the effective stack height at Sioux was 100m above the inversion ceiling at practically any level of operation. For the neutral stability iteration, the plume could penetrate most of the inversion ceiling; whereas 100% of the emission would be caught beneath the inversion ceiling at lowest output, only 50% would be trapped at highest output on Sioux. On the iterations with 4 (a) stability, there is no way the plume can penetrate the 490 m. mixing depth at the wind speed specified.

Because many units had stack heights and plume rise factors in the range where shifting from light to full load could make a large difference in the fraction of the emission trapped beneath the 295 m. inversion ceiling, most of the units had declining marginal costs. Meramec 4 (see Figure 2-8) is an outstanding example. When these combined cost functions were approximated by another piece-wise approximation to within

2.5%(1), one to three integer variables were required per unit, to a total of 26. (Recall, however, that exactly one of the integer variables for each unit is non-zero.)

A final parameter required is the hourly demand for power from steam-electric power plants in the PPSR. Because of the difficulty described previously in treating the demand experienced by the Illinois Power Company (recall that only a share of its customers are in the St. Louis area) the assignment is slightly arbitrary. Since meteorology for Case 1 represents mid-morning conditions, mid-morning demands for electric power are needed. Assuming that present typical mid-morning loads of Union Electric (2150 mw, November 1968) and Illinois Power (600 mw (2)) will increase 9% by Winter 1969-70, and subtracting an estimated 150 mw to be generated by hydroelectric power, a reasonable late Autumn or Winter weekday demand on St. Louis area power plants would be about 3000 mw. This net load of 3000 mw is used as the basis for Problem 1.

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(1) One function could be approximated only within 5% with three integer variables.

(2) About 64% of the generating capacity of Illinois Power is located at Wood River, within the PPSR. Assuming that the same fraction of its load falls within the PPSR, and that it has approximately the same weekday load in proportion to capacity as Union Electric, the 600 mw estimate is obtained.

4.2.3 DISCUSSION OF NUMERICAL RESULTS

With the foregoing specifications, the model was operated for Case 1, Problem 1. The results -- power dispatched to each unit, value of the pollution exposure function, fuel cost function, and combined cost function are shown in Table A-1. Subproblem (a) assumes D = \$.10; subproblem (b) dispatches without regard to the social cost of pollution exposure by setting D = 0. Not surprising, the Cahokia or Ashley units were not dispatched under either subproblem, nor, in fact, for any of the problems for which the model was run. Being old and inefficient, and centrally located, these units are unattractive by either set of standards. "Pollution exposure units" on this and subsequent Tables are person-ppm-hr (SO_2). The cost per additional megawatt, indicated at the bottom of the page, is the amount by which each cost function would change if gross power demand were increased by 1 mw, and the integer variables were fixed. It is the marginal combined cost that can be used for a utility to decide whether it is cheaper at any point to produce additional power within the system, or buy it from another company. If the exposure cost were really a tax the utility had to pay (perhaps in lieu of some other charge) so that pollution costs were inserted into the company's cost structure, then this marginal combined cost would be the basis for quoting a sale price to other utilities. Such a price structure would allow utilities to buy and sell power with proper regard for air pollution exposure in their respective metropolitan areas.

The approximate solution, the last line on Tables A-1 to A-7, serves as a check on the mixed-integer programming solution. It is obtained by ranking all units according to increasing average combined cost. One proceeds down the list dispatching all units except possibly the last, to capacity, until the gross power demand is met. It is assumed that the cost curve on the last unit dispatched is linear and of only one sement. If all units have increasing marginal costs, then the approximate solution will give a rather inefficient dispatching procedure, and the value will be above that obtained by programming.

4.2.4 DISCUSSION OF GRAPHICAL RESULTS

From Table A-1 it is still difficult to visualize and evaluate the operation of the model. To study the operation of the model in detail, maps C-4 to C-9 were prepared for case 1.

Concentration

A preliminary scan of expected concentration indicated that most values would fall below 5 parts per hundred million (pphm) SO_2. This value was picked as a convenient maximum for the range of regular symbolism. Because of the exponential form of the Gaussian diffusion model, the concentration three standard deviations from the downwind axis of a plume will have an expected value of only 1% of the axial value. In order to obtain detail on a contour map at these low concentrations without cluttering the map with contour lines, it was advantageous to use an exponential scale for map symbols; the widths were in the ratio 1:1:2:4:8:16. Since it was desired that essentially zero-level concentrations might be distinguished from other low values, .01 pphm was taken as a threshhold concentration for display purposes, and lesser concentrations were represented by a background of hyphens (the lightest background employed on the map). Above the threshhold, the widths of the levels of symbolism were in the ratio 1:1:2:4:8:16. The range for each level of symbolism is set forth below each map. On the six maps showing concentrations, areas in which the SO_2 concentrations exceeded 1.0 pphm are shown by an X or a darker symbol. For ease in reading the map, Illinois coordinates (the system used for air pollution data) are given every 50,000 feet along the map border, with X's at the intermediate 25,000 feet.

First consider map C-5, (3) concentrations with lowest combined cost dispatching. Most of St. Louis City and all of East St. Louis fall below this level, whereas the southern part of St. Louis county, Granite City, and Alton all have high concentrations -- the latter two in the range of 2.5-5.0 pphm. The fact that emissions are at some distance above ground level is clearly shown by the pattern of concentrations downwind of Meramec, Wood River, and Labadie. Ground level concentrations do not exceed the threshhold level until a downwind distance of about 30,000 feet is attained. Some caution should be exercised in interpreting variations on a scale much smaller than 20,000 feet (10,000 feet in the cities of St. Louis and Alton),for these distances are the grid sizes. (The regularly-spaced numerals on Map C-3 indicate the locations of grid cells.) Though the interpolation algorithm [37] is non-linear, it was not designed particularly to interpolate on the sum of Gaussian functions. The general north-northeast orientation of the Wood River plume is due to the combination of south and south-southwest winds in Case 1.

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(3) Map C-5 also appears on the cover at a somewhat larger scale.

The preceeding map, C-4 shows expected concentrations under conventional lowest fuel cost for the same meteorlogical case and the same net demand than C-5. Values on map C-4 are roughly one level above corresponding values on C-5, indicating that concentrations on C-4 must be generally twice as high. Extreme peaks (above 5.0 pphm) are denoted by the letter H on Map C-4, and appear light in color, since they are encircled by the black symbolism denoting the highest level of regular symbolism. Notice that the locations of the Venice and Wood River plants are particularly unfortunate with regard to air pollution: they create very high levels of pollution over Alton and Granite City (10.0 pphm SO_2 is the peak over Granite City.)

One of the great advantages of computer mapping is that it permits the quantitative comparison of two surfaces. Map C-6 shows the SO_2 concentrations under dispatching without regard to "social cost", minus the concentration obtained under load shifting, or the improvement from the load-shifting model. It is evident from the map that Granite City (the peak just north of the Venice plant) benefits most from load-shifting, and that Alton and southern St. Louis County benefit to a lesser extent. The data value extremes printed below the map show that the improvement in concentrations rose to as high as 4.24 pphm, and extended in a wide band northward from the center of the core to the edge of the PPSR. The behavior of the Labadie plant is particularly interesting. Since the plant is located far west of the populated metropolitan core, it ought to be used as intensively as possible, in order to minimize pollution exposure. Table A-1 shows that the Labadie unit (abbreviated LA) is operated at capacity output when a penalty is attached to pollution emissions. Because the plume exit velocity is greater at capacity output than at lower outputs, the plume rises higher. Areas within about 50,000 feet of the plant experience smaller air pollution concentrations under combined-cost minimization -- indicated by the region of dots north of Labadie on Map C-6.

One of the interesting characteristics of this diffusion section of this model is the fact that increasing output can actually decrease downwind concentrations in some locations. Finally, the reader may notice that the range of data on this "improvement" map does include negative values: their magnitude remains below the trivial magnitude of .02 pphm, however. Map C-6 does not distinguish zero and negative values; inspection of the data from which Map C-6 was drawn shows that there is, indeed, a slight deteriorization of SO_2 concentrations at vertical coordinate 800. But this increase in concentration of .02 pphm in a rural area is a tiny price to pay for an improvement of 5 pphm in the populated centers of Granite City and Alton.

Density of Exposure

Finally, it should be noted that it was not really ground-level SO_2 concentrations, but rather population exposure to SO_2, that was to be reduced by the load-shifting model. To that end, two maps of the density of exposure to SO_2 ([population density in persons/square mile] x SO_2 concentration in ppm) were prepared: Map C-7, dispatching based on fuel costs alone, and Map C-8, dispatching to minimize total "combined cost". Map C-7 indicates the region in which electric power generation helps cause an air pollution "problem", a high density of exposure to pollution.

The entire metropolitan core, including Alton and Granite City, is severely affected. The influence of the Meramec plant is particularly serious; although the highest concentrations occur about 20 miles south of St. Louis, the whole city experiences a high density of exposure; in fact, the peak exposure density occurs about one mile north of downtown St. Louis, where the population density is greatest. Juxtaposition of Map C-5 (concentrations) and Map C-7 (exposures) indicates that since East St. Louis, Illinois has only moderate levels of air pollution concentration, its very high levels of exposure must be due to very high population density(4). On these density of exposure maps, a dark H, with a slash overprinted, signifies exposure densities above the nominal maximum specified for regular symbolism--200 persons-ppm/sq.mi.

The density map under optimal combined cost dispatching, Map C-8, shows that the entire northern half of the PPSR is still affected by pollution from power plants, and that Alton and Granite City have significant exposure densities.

Finally, Map C-9, better than any other single map, summarizes the results of the load- shifting model for the southerly wind case. The comparison of Map C-9 with C-7 reveals that all the areas seen earlier to experience heavy exposure under fuel cost dispatching--Alton, St. Louis, East St. Louis--now enjoy substantial improvements. Overall, the patterns of the two maps are similar; the improvement map is about one level lower--indicating the 50% reduction in exposure which necessarily accompanies the corresponding reduction in concentrations. The northward shifting of maximum concentrations above the Labadie plant under combined cost dispatching is again evident. Finally, East St. Louis stands out notably, as exposure density there is improved by more than 50%.

4.2.5 Analysis of Results

Another evaluation of the results of the load-shifting model is Table 4-2 (based on Tables A-1 and A-2), in which the results

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(4) Reference to Map C-3 of population density confirming this reasoning.

TABLE 4-2

SUMMARY STATISTICS: TOTAL FUEL COSTS AND SO_2 POLLUTION EXPOSURE UNDER OPTIMAL DISPATCHING

CASE 1 - MODERATE SOUTHERLY WIND

Value of SO_2 Exposure Unit	Fuel Cost $/hr (Difference)	Pollution exposure person - ppm SO_2 - hr (Difference)
PROBLEM 1: Net power demand = 3000 mw		
D = .1	6755	21052
	(-565)	(21675)
D = 0	6190	42727
PROBLEM 2: Net power demand = 2000 mw		
D = .1	4027	740
	(-167)	(15060)
D = 0	3860	15800

are considered not only on the basis of population exposure, but also from the point of view of operating cost. The maps C-4 to C-9, just discussed, apply to Problem 1, with a net power demand of 3000 mw. Note that, over the entire PPSR, population exposure has been reduced by 21675/42727, about 51%, at a surprisingly small increase in fuel and maintenance costs: 9.1%. Turning again to Table A-1, it is now clear that the reduction in exposure in St. Louis city occurred mainly from shifts on the Meramec units: units 1 and 2 were shut down entirely, and unit 4 was increased to full capacity, so as to be able to break through the inversion ceiling to the greatest possible extent. Similarly, instead of loading each of the Venice groups to about two-thirds capacity, units 5 and 6 are increased to full load and units 1-4 reduced as much as possible. To compensate for these adjustments, Wood River 1-3 and Sioux 1 were both increased to full load.

I should note that the extraordinary responsiveness of the model in case 1, problem 1, far exceeded my expectations. With the outages postulated, the total power system in the PPSR had a gross capacity of only 4100 mw, of which over 3100 mw needed to be dispatched; it was thought that the system would have little flexibility. It was reasoned that, the more nearly a system's demand approached its capacity output, the fewer choices left the dispatcher to select which units might be partly or totally shut down. On the other hand, if demand is light, then considerable reduction in pollution exposure may be achieved at very nominal cost. The load-shifting model gives most dramatic results when it shifts from one unit to another with slightly higher fuel costs but substantially lower pollution costs. The shift from Meramec units 1-2 to Sioux, Labadie and Meramec 4 in case 1, problem 1 was of this dramatic nature.

4.2.6 Problem 2, A Holiday

Deriving Holiday Peak Demand

In order to see whether the model responds with this type of behavior, case 1, problem 2 was solved; the meteorological conditions were those of problem 1, but the power demand was only 2000 mw. From Chapter 1, it can be seen that peak hourly net demand on a holiday or Sunday is about two-thirds the corresponding weekday demand. The lower portion of Table 4-2 summarizes the extremely dramatic behavior of the model in problem 2. Pollution exposure may be reduced by 95% at an additional fuel cost of $167 per hour--an increase of only 4.4%. Table A-2 details the operating conditions on each plant for this problem. For part (b) of the problem, the Meramec plant is dispatched before Wood River units 1 to 3. But sufficient capacity exists among the Wood River, Sioux, and Labadie units, even with the outage, so that the model can afford to dispatch only plants north or west of the St. Louis center, which cause negligible pollution exposure.

Case 1 was dramatic both because of the limited mixing depth and the location of plants in relation to the wind and city. Under stability class 4(b), the mixing depth is 295 m. This is a depth that plants could mostly penetrate at full load, but be trapped underneath at light load.

4.3 CASE 2--LIGHT WESTERLY WIND

4.3.1 Meteorological Conditions

Because of the several factors affecting the model behavior, it is appropriate to apply the model under alternative situations. Thus meteorological case 2, a light westerly wind, was defined with the parameters in Table 4-3. The very light surface wind (about 5 mph) in case 2 was deliberately chosen to compensate for the possible overestimation of wind speeds aloft (see section 2.4.6).

In general, the model was much less responsive in case 2 than in case 1, for there are no major generating facilities downwind (east) of St. Louis(5). In addition, because of the unstable diffusion conditions, the average maximum mixing depth is typically higher in Case 2 than in case 1 conditions, and therefore more difficult to penetrate by hot plumes.

4.3.2 Graphical Discussion of Results

The set of maps C-10 through C-15, of the same types as C-10 to C-15, for case 1, problem 1, was prepared. Map C-10, showing concentrations under dispatching without taking social cost into account demonstrates that peak concentrations for case 2, problem 2 are not as extreme as for case 1, problem 1. Not only do the plumes on Map C-10 fail to overlap like those on Map C-5, but also power generation is only two-thirds as large as for

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(5) The large (600 mw) Baldwin plant, to be located about 35 miles SE of downtown St. Louis and scheduled to begin operation July 1970, could make a large improvement in case 2 if provision were made for it in the model. It was omitted from the model, however, for a lack of specific information and for a late opening date.

TABLE 4-3

CASE 2 - LIGHT WESTERLY WIND

DISTRIBUTION OF METEOROLOGICAL PARAMETERS

Stability Class	Number[40]	Mixing Depth
Slightly unstable	3	490

Wind Direction	Frequency
West	.75
West-northwest	.25

Wind speed

2.2 m/sec

Representative Period

Nov. 8, 1964 7 a.m. to 1 p.m.

case 1, problem 1. Map C-10 indicates that the Labadie plant raises SO_2 concentrations over the entire city of St. Louis by somewhat under .17 pphm. The western portion of St. Louis County (east of Labadie) experiences moderately high concentrations. It is evident that under the west wind, emissions from the Sioux plant affect Alton, and those from the Wood River plant, the cities of Wood River (just east of the plant) and Edwardsville (about 10 miles further southeast).

Map C-11 shows concentrations under optimal combined cost dispatching. Because pollution from Labadie is caught under the inversion ceiling and blows eastward over most of the populated core, considering its "social cost" leads to a reduction in the Labadie load and an increase at Meramec.

Map C-12 shows improvement in SO_2 concentrations, using the load-shifting model under case 2. The improvement is greatest near Wood River, although moderate improvement extends southeast over Edwardsville. Because of a reduction at the Labadie plant, most of St. Louis County, St. Louis city, and Madison County obtain a slight improvement from load shifting. The area which receives higher concentrations under load shifting than under traditional dispatching is, as expected, in a region downwind of the center of the PPSR--south-central St. Clair county (around coordinates 550 h, 600 v).

Map C-13 of density of exposure to SO_2 depicts the location of the air pollution exposure problem; most of St. Louis city has moderate exposure densities. Alton (just east of Sioux) and

Edwardsville, southeast of Wood River, obtain still higher exposure rates, and the city of Wood River is worst. Under optimal combined-cost dispatching, map C-14, population exposure follows a generally similar pattern, but is reduced at St. Louis city and Edwardsville at the expense of higher exposure densities in St. Clair County, east of Meramec. Finally, Map C-15 shows improvement in exposure densities from the load-shifting model in case 2, problem 2. The geographic areas of greatest improvement are first, Wood River; second, Edwardsville; and third, the North side of St. Louis City. Of areas without improvement, the south-central part of St. Clair county probably had slightly higher exposure densities. The "Data Value Extremes" below the map title show that density of SO_2 exposure was improved by as much as 93.44 person-ppm per sq.mi., and increased by no more than 12.74. By integrating this map of improvements or increases in exposure densities over the approximately 7000 sq.miles in the PPSR, one would obtain the amount of the improvement in exposure. Finally, reference to Table A-4 shows the load shifting to accomplish these improvements --simply a decrease at Labadie and corresponding increase on Meramec units 1,2,and 4.

It should be noted that this load-shifting model is not the only means of reducing population exposure; in fact, it is a relatively untried approach. The more common approach is to reduce emissions of the pollutant.

4.3.3 Numerical Analysis of Results

Table 4-4 shows summary statistics for the West Wind case.

TABLE 4-4

SUMMARY STATISTICS: TOTAL FUEL COSTS AND SO_2 POLLUTION EXPOSURE UNDER OPTIMAL DISPATCHING

CASE 2 - LIGHT WESTERLY WIND, NORMAL COAL

Value of SO_2 Exposure Unit	Fuel Cost $/hr (Difference)	Pollution exposure person - ppm SO_2 - hr (Difference)
PROBLEM 1: Net power demand = 3000 mw		
D = .1	6192	23768
	(-8)	(240)
D = 0	6184	24008
PROBLEM 2: Net power demand = 2000 mw		
D = .1	3921	13967
	(-68)	(2797)
D = 0	3853	16764

Note that for problem 1, very little improvement could be obtained from load shifting (nor would much money be spent). Table A-3 shows the dispatching levels (a) with, and (b) without consideration of the social cost of exposure. The adjustments to control pollution consisted of shifts to obtain greater stack height wherever possible. Basically, though, the same plants were kept in operation under subproblems (a) and (b).

As was expected, the load-shifting model was more responsive in case 2, problem 2 (westerly wind, 2000 mw net demand). From Table 4-4, it can be seen that a decrease of 2797 exposure units, or about 16.7% is obtainable by load shifting, at an extra fuel cost of $68, about 1.7%. Although this certainly is less dramatic than the improvements obtained in case 1, case 2 is still worth examining further.

4.4 CASE 3

4.4.1 Results Under Control of Sulfur Oxide Emissions

Beginning with the winter of 1970-71, various state and local regulations will limit sulfur dioxide emissions from power plants in the PPSR. In appendix B.2, I describe possible control measures the two electric power utilities might take in compliance with these regulations, and the resulting fuel and pollution curves under case 2 meteorological conditions.

The combination of this new set of exposure and fuel cost functions with case 2 meteorological data was labeled case 3. The summary statistics for case 3, Table 4-5, indicate that load shifting can reduce air pollution exposure even beyond the level

TABLE 4-5

SUMMARY STATISTICS: TOTAL FUEL COSTS AND SO_2 POLLUTION EXPOSURE UNDER OPTIMAL DISPATCHING

CASE 3 - LIGHT WESTERLY WIND. Dolomite stack gas cleaning process or low sulfur coal used as required

Value of SO_2 Exposure Unit	Fuel Cost $/hr (Difference)	Pollution exposure person - ppm SO_2 - hr (Difference)
PROBLEM 1: Net power demand = 3000 mw		
D = .1	7894	11620
	(-19)	(848)
D = 0	7875	12468
PROBLEM 2: Net power demand = 2000 mw		
D = ∞[a]	5738	3683
	(-865)	(4608)
D = .1	4873	8291
	(-17)	(234)
D = .05	4856	8525
	(-5)	(1)
D = 0	4851	8526

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[a] Fuel cost was omitted and air pollution minimized.

accomplished by low sulfur fuel alone. For case 3, problem 1, for example, a reduction of 848 exposure units, or 6.8%, is obtained an an increased fuel cost of $ 19 per hour, or 2.5%.

Case 3, problem 2 demonstrates that reductions in air pollution exposure through load shifting are not always greater at a light load (2000 mw) than at a heavy load. Table 4-5 indicates that the increase in fuel costs through considering air pollution exposure cost (evaluating one exposure unit D = $.10) in the optimal combined-cost solution is $22. per hour, slightly more than the corresponding increase in problem 1. Yet the decline in air pollution exposure is only 235 units, compared to 848 units in problem 1. As seen in Tables A-5 and A-6, the advantage at the higher load comes from slightly improved dispatching of Wood River units 1-3, and Venice groups 1-4 and 5-6 under the higher load to reduce under air pollution exposure. At the lower (2000 mw) load, these groups of units need not be dispatched at all.

To examine further the behavior of the load-shifting model in this case, problem 2(c), considering only air pollution exposure costs (D is infinite), and problem 2(b) evaluating one pollution exposure unit at the intermediate level of D = $.05, were solved. From Table 4-5, it is clear that for case 3, problem 2, load shifting effects the greatest improvement in air pollution exposure when the cost of one exposure unit is considered important in relation to fuel costs. The reasons are best understood by considering Tables A-6 and A-7. An increase in the value assigned to one pollution exposure unit from 0 to \$.05 alters dispatching only by shifting about 40 mw generation from Sioux 1 to Wood River 5. Increasing this parameter further to D = \$.10 causes some readjustments in all units except Labadie and Meramec 3. The major change in air pollution exposures occurs when the fuel cost is given no consideration. Then Labadie is taken off line and the necessary power generated from the Venice units. The cost functions for case 3 assume minimal compliance with air pollution control regulations expected to be in effect by the winter 1970-71, and thus assume no controls on the Labadie plant, located in Franklin County. Nevertheless, with a light westerly wind, and with sulfur emissions from all other power plants controlled, over 50% of the PPSR's air pollution exposure would be due to Labadie (problem 2(d)). Paying the additional cost of switching from uncontrolled emissions at Labadie to controlled emissions at Venice reduces exposure substantially under these conditions(5).

4.4.2 Trade-off Between Fuel and Exposure Costs

Figure 4-1 portrays the trade-off between fuel costs and exposure to sulfur dioxide under case 3. As expected, the greater the amount spent on fuel costs, the greater may be the reduction in air pollution exposure. With any particular system of generating facilities and meteorological conditions, there is an

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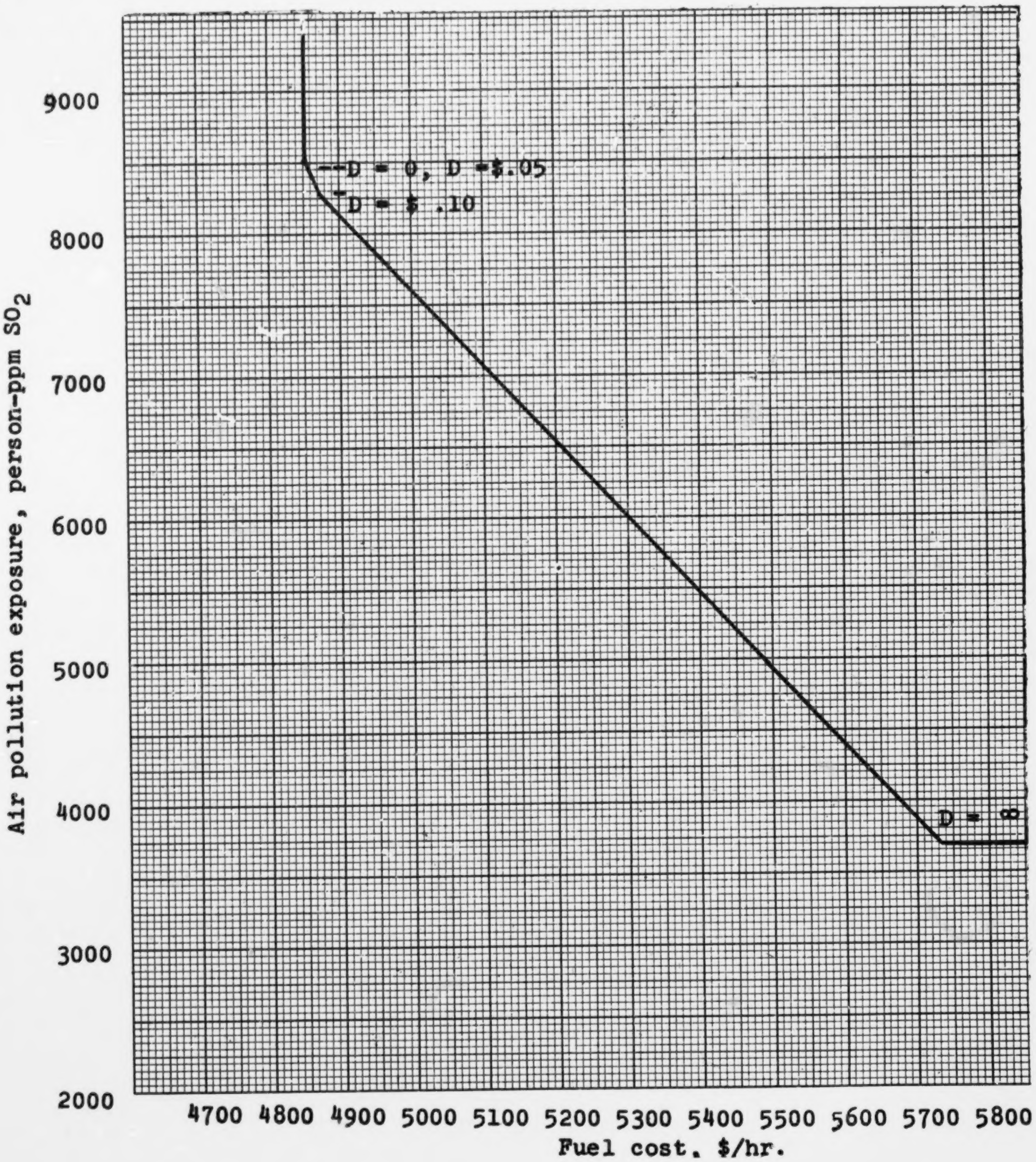
(5) A more reasonable solution, but beyond the context of problem 2(c), would be to operate Labadie with low sulfur coal or stack gas cleaning instead of the Venice units.

FIGURE 4-1

COST CURVE TRADE-OFF BETWEEN
FUEL COST AND AIR POLLUTION EXPOSURE
(CASE 3, PROBLEM 2, BASED ON TABLE 4-5)



unavoidable minimum amount of air pollution exposure and an irreducible minimum fuel cost. These bounds are the horizontal and vertical lines, respectively, on the curve in Figure 4-1.

Although I have connected the vertices from solutions of the model by straight line segments, it is not necessarily true that the system has a dispatching pattern to reach every point on the line. Declining marginal costs mean that certain discontinuities on the curve of lowest fuel and air pollution cost are unavoidable(6). The general shape of the curve will be, however, as indicated.

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(6) The integer programming formulation of problem 2(c) contained 22 integer variables, or 8 instances of declining marginal pollution exposure cost.

CHAPTER 5

CONCLUSIONS

5.1 SENSITIVITY OF THE MODEL

From these initial evaluations, I may state a number of conclusions on the applicability of a load-shifting model to reduce exposure to pollution from power plants. The general shift to plants downwind of population centers would hold regardless of the form of the load-shifting model. Changing loads to break through the inversion ceiling, and considering total exposure rather than peak concentrations, are unique to this model(1).

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(1) A review of relevant air pollution literature has brought two examples of load-shifting models to my attention. One reference ([9], p. 24) demonstrates the lower cost in applying population control measures to plants upwind of population centers. The other example is a detailed examination as part of a systems analysis approach to pollution abatement in Chicago, being developed jointly by the Argonne National Laboratory, Chicago Department of Air Pollution Control, and the National Center for Air Pollution Control ([10], Chapter 6). My approach has differed from this Chicago study in the following matters:

1. The Chicago model is intended to be used only for abatement during "incidents" and not as a routine matter throughout the winter;
2. The Chicago Study does not consider pollution "exposure" integrated over a region, but seeks only to keep peak SO_2 concentrations at specified receptors below specified levels;
3. Least squares regression is used to make power output a linear function of heat input and emissions;
4. Ground level concentrations are assumed to be proportional to emissions. Thus the possibility of declining marginal costs is ruled out.

(continued on following page)

5.1.1 Sensitivity to Meteorological Factors

First, the extent to which exposure may be reduced, and the accompanying dispatching pattern and cost to the power system, depend heavily on meteorological factors--especially wind speed, direction and mixing depth. If the wind direction is such that there is a substantial quantity of generating capacity downwind of populated areas, then the load-shifting model will conclude that very low exposure to air pollution is obtainable, particularly under only moderate demand for power. Because of the location of the Wood River and Sioux plants, southerly winds meet this condition for the St. Louis area. If the mixing depth is quite low, then plumes from power plants can effectively penetrate the inversion lid, and ground level concentrations will not be a problem, except, possibly, at the break-up of the inversion. The load-shifting model gives most dramatic results for a moderately low inversion height (between 200 and 300 meters). Under moderate winds, plumes from the larger plants generally penetrate inversions of this height if operating at full load, but are trapped beneath the inversion if operating at a light load. In these cases, the load-shifting model demonstrates that shifting among units, in addition to shifting among plants, can substantially decrease exposure to air pollution. If, on the

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(1), continued

5. Load-shifting is part of a larger abatement model which includes short term fuel shifts to natural gas.

6. The abatement problem may be formulated entirely as a linear programming problem and solved by the Simplex procedure.

other hand, the mixing depth is high, then plumes will not be able to penetrate the inversion ceiling regardless of the load on the generating unit.

Wind speed has a mixed effect on the operation of the model: high wind speeds favor the spreading of the pollution over a greater downwind distance and possibly over an area of lower population density, than light winds. On the other hand, high wind speed inhibits plume rise, and may cause plumes to be trapped beneath the inversion ceiling, resulting in much higher ground-level concentrations. Which of these factors will predominate in a specific case can be determined by operating the model.

5.1.2 Sensitivity to Power Demand

The demand for power from steam-electric generating plants also affects the possible extent and cost of exposure reduction through load shifting. In general, the lower the load, the more choice there will be in dispatching generating units, and the greater the shift possible to reduce exposure from power plant emissions. There are, however, exceptions to this rule: particularly if high sulfur coal or stack gas cleaning processes are being used on selected plants only, there may be substantial cost differences in load shifting from plants with uncontrolled to controlled sulfur oxide emissions. Therefore, the load-shifting model may give significant decreases in pollution exposure even with moderately high loads (such as 3000 mw for the St. Louis PPSR).

5.2 GENERAL EVALUATION OF THE MODEL

From the experience of solving the model explicity in a few cases, I have found that the load shifting could offer reductions in pollution exposure as defined herein of up to 95% with less than a 5% increase in fuel and maintenance costs in the most favorable circumstances. Under conditions less favorable for load shifting, an exposure reduction of only 17% is obtained, but at an increased fuel cost of less than 2%. In most cases, then, the load-shifting model can attain moderate reductions in air pollution exposure, and under a few cases, it can accomplish quite remarkable reductions.

The critical assumptions of the model were (1) a linear damage function could be used to aggregate the effect of the distribution of SO_2 concentrations over a certain distribution of population; and (2), that a Gaussian diffusion equation, with modifications by Turner for limited mixing depth, could be used as the basis for predicting diffusion from power plant stacks. To refine the model further, a number of steps might be taken. Because of the importance of meteorological parameters, it would be valuable to obtain some type of wind speed, direction, and temperature gradient measurements aloft. (These are necessary for determining the mixing depth and atmospheric stability.) By means of photographs, the plume rise equation and multiple-stack effect might be calibrated to each power plant. Finally, though most difficult, the effect of local topography might be included. By constructing a diffusion model with a variable wind field, some of the eddies due to the urban heat island, and to the channeling effect of the Mississippi River and the adjacent low-lying American Bottoms, might be included in the diffusion model.

An immense amount of research is needed in order to determine precisely the effects of various concentrations of individual pollutants, and of typically occurring combinations in an urban atmosphere. A detailed pollution exposure "damage function" could not be specified until such research is completed. On the other hand, a load-shifting model permits an approach to reduce exposure to pollution which involves no major changes in operating procedure for the electric power industry, and no capital investment. As more is learned about the effects of exposure to sulfur dioxide, its decay products, and about other air pollutants, the load-shifting model is easily modified to find least "combined cost" solutions under these new conditions.

5.3 APPLICATIONS

5.3.1 Daily Operation

Useful applications of a load-shifting model such as I have described here are several. Most obvious, after the diffusion model had been suitably refined and tested, the model could be put into daily operation in the winter(2) in the St. Louis area. To convert the air pollution exposure function into a real cost function, a tax on emissions of sulfur dioxide could be levied by a regulatory agency, where the amount of the tax would as nearly as possible approximate the "damage" caused by the emission. Thus, it should take into account geographical location, meteorological factors, and effective height of emission. Alternatively, a quota system could be used instead of a direct tax: each day, week, or month, the electric power companies could be allotted a certain quota of "air pollution exposure units", and each emission would be counted against that quota in proportion to the air pollution exposure it created (its social cost). If the utility exceeded its quota, it would be fined; it if controlled in excess of its quota, the unused units would carry over into the next control period. Setting the quota properly would mean the utility would avoid fines by operating with concern for pollution exposure.

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(2) Demand is so high during most of the summer months that little change could be made through load shifting. In addition, the absence of space heating and improved dispersion conditions make air pollution concentrations much lower from mid-spring to mid-autumn.

An immediate extension of the above program would be to establish exposure quotas on particulate and nitric oxide emissions in the same manner.

5.3.2 Conceptual Applications

Beyond its immediate application, however, this load-shifting model has numerous conceptual uses in making decisions about electric power. Even if daily operation of dispatching did not use the load-shifting model, the model would still be valuable in measuring the contribution of a switch to low sulfur coal, installing the calcium/dolomite or some other stack gas cleaning process, the relative air pollution effects of alternative locations for new power plants, or the effects of stacks of different heights, diameters, and different exit gas velocities. It would be very easy for the load-shifting model to evaluate for example, the relative effects of generating with a plant using a stack gas cleaning device at a plant upwind of a populated area, or producing a greater volume of pollution at a plant with a lower standard of controls at a downwind location. For a unit with a choice of operating procedures, several cost functions for the unit may be included in the mixed-integer programming formulation, with the added requirement (specified by an integer variable) that only one of the functions be used at a time.

5.3.3 Evaluation of Investments

For conceptual applications involving capital investment in air pollution control equipment, a simulation of the power system should be made for a year, or the entire lifetime of the investment by solving the dispatching model for a number of representative meteorological and load cases. The fraction of time the unit with the proposed investment would be used, and its reduction to operating costs, could be matched against the capital and debt costs of the investment.

5.3.4 Applications to Other Industries

Finally, although this model has talked only about the electric power industry, load shifting would also be possible in other industries with many plants in the metropolitan area-- incineration or chemicals, in particular. Since most industries could not shift as readily from one plant to another; and also because their product can be stored for some time (so the requirement that demand be met would not be absolute), the load-shifting would more likely take the form of shutting those plants which cause the most severe exposure to air pollution.

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APPENDIX A

OPTIMAL LOAD DISPATCHING AND COSTS FOR ST. LOUIS POWER PLANTS

TABLE A-1

Optimal load dispatching and costs for St. Louis power plants
Dispersion Case 1: Moderate Southerly wind, moderately unstable
Problem 1: Net Power Demand of 3000 mw

Costs are per hour

	a) Pollution exposure unit valued at $.10				b) Pollution exposure unit valued at $0.			
Plant and Units	Gross Generation, mw	Pollution Exposure Units	Fuel Cost $	Objective Function $	Gross Generation, mw	Pollution Exposure Units	Fuel Cost $	Objective Function $
S 1	250.0	31.8	450.0	453.2	250.0	31.8	450.0	450.0
S 2	531.0	37.7	1195.0	1198.8	424.8	37.6	773.1	773.1
C 1-4	-	-	-	-	-	-	-	-
C 5-6	-	-	-	-	-	-	-	-
V 1-4	37.0	1400.3	88.8	228.9	219.1	7743.6	537.8	537.8
V 5-6	213.0	6141.8	554.0	1168.2	142.0	4476.3	345.0	345.0
M 1-2	-	-	-	-	255.6	15144.1	533.0	533.0
M 3	150.0	5943.3	289.0	883.3	150.0	5943.3	289.0	289.0
M 4	355.0	5613.1	796.5	1357.8	319.5	6792.7	634.4	634.4
AS	-	-	-	-	-	-	-	-
W 1-3	471.0	306.9	1036.8	1067.5	376.8	983.7	782.5	782.5
W 4	104.0	1211.5	189.8	310.9	104.0	1211.5	189.8	189.8
W 5	396.0	299.0	727.4	757.3	396.0	299.0	727.4	727.4
LA	620.0	66.8	1427.6	1434.3	496.0	63.5	927.5	927.5
Total:	3127.0	21052.2	6754.9	8860.2	3133.8	42727.1	6189.5	6189.5
Cost/add'l mw.:		40.3	2.56	6.52		27.9	2.66	2.66
Approx. solution:				8857.0				6959.1

TABLE A-2

Optimal load dispatching and costs for St. Louis power plants
Dispersion Case 1: Moderate Southerly wind, moderately unstable
Problem 2: Net Power Demand of 2000 mw

Costs are per hour

	a) SO_2 pollution exposure unit valued at $.10				b) Pollution exposure unit valued at $0			
Plant and Units	Gross Generation, mw	Pollution Exposure Units	Fuel Cost $	Objective Function $	Gross Generation, mw	Pollution Exposure Units	Fuel Cost $	Objective Function $
S 1	250.0	31.8	450.0	453.2	250.0	31.8	450.0	450.0
S 2	424.8	37.6	773.1	776.9	424.8	37.6	773.1	773.1
C 1	--	--	--	--	--	--	--	--
C 5	--	--	--	--	--	--	--	--
V 1	--	--	--	--	--	--	--	--
V 5	--	--	--	--	--	--	--	--
M 1	--	--	--	--	--	--	--	--
M 3	--	--	--	--	150.0	5943.3	289.0	289.0
M 4	--	--	--	--	248.5	7366.0	481.4	481.4
AS	--	--	--	--	--	--	--	--
W 1-3	471.0	306.9	1036.8	1067.5	47.0	599.5	95.4	95.4
W 4	--	--	--	--	104.0	1211.5	189.8	189.0
W 5	396.0	299.0	727.4	757.3	356.4	546.4	644.5	644.5
LA	533.7	65.0	1039.3	1045.8	496.0	63.5	927.5	927.5
Total:	2075.5	740.3	4026.6	4100.7	2076.7	15799.6	3859.7	3859.7
Cost/add'l mw:		.04	3.05	3.05		13.4	2.16	2.16
Approx. solution:				4464.5				4249.2

TABLE A-3

Optimal load dispatching and costs for St. Louis power plants
Dispersion Case 2: Light Westerly wind, unstable
Problem 1: Net Power Demand of 3000 mw

Costs are per hour

	a) Pollution exposure unit valued at $.10				b) Pollution exposure unit valued at $0.			
Plant and Units	Gross generation, mw	Pollution Exposure Units	Fuel Cost $	Objective Function $	Gross Generation, mw	Pollution Exposure Units	Fuel Cost $	Objective Function $
S 1	250.0	2048.4	450.0	654.8	250.0	2048.4	450.0	450.0
S 2	424.8	3463.0	773.1	1119.4	424.8	3463.0	773.1	773.1
C 1	0	0	0	0	0	0	0	0
C 5	0	0	0	0	0	0	0	0
V 1	187.1	1692.5	457.8	627.0	184.4	1667.4	451.0	451.0
V 5	106.5	944.7	256.3	350.7	127.8	1137.0	309.5	309.5
M 1	284.0	979.0	609.6	707.5	255.6	857.9	533.0	533.0
M 3	150.0	407.8	289.0	329.8	150.0	407.8	289.0	289.0
M 4	319.5	914.9	634.4	725.9	319.5	914.9	634.4	634.4
AS	0	0	0	0	0	0	0	0
W 1-3	423.9	3983.8	899.6	1298.0	423.9	3983.8	899.6	899.6
W 4	93.6	1126.9	166.8	279.5	104.0	1320.6	189.8	189.8
W 5	396.0	3276.9	727.4	1055.1	396.0	3276.9	727.4	727.4
LA	496.0	4930.3	927.5	1420.5	496.0	4930.3	927.5	927.5
Total:	3131.4	23768.2	6191.5	8568.2	3132.0	24008.0	6184.3	6184.3
Cost/add'l mw:		9.28	2.50	3.43		9.28	2.50	2.50
Approx. solution:				9085.6				6654.9

TABLE A-4

Optimal load dispatching and costs for St. Louis power plants
Dispersion Case 2: Light Westerly wind, unstable
Problem 2: Net Power Demand of 2000 mw

Costs are per hour

	a) Pollution exposure unit valued at $.10				b) Pollution exposure unit valued at $0			
Plant and Units	Gross Generation, mw	Pollution Exposure Units	Fuel Cost $	Objective Function $	Gross Generation, mw	Pollution Exposure Units	Fuel Cost $	Objective Function $
S 1	250.0	2048.4	450.0	654.8	250.0	2048.4	450.0	450.0
S 2	424.8	3463.0	773.1	1119.4	424.8	3463.0	773.1	773.1
C 1	0	0	0	0	0	0	0	0
C 5	0	0	0	0	0	0	0	0
V 1	0	0	0	0	0	0	0	0
V 5	0	0	0	0	0	0	0	0
M 1	227.2	752.1	467.1	542.3	0	0	0	0
M 3	150.0	407.8	289.0	329.8	150.0	407.8	289.0	289.0
M 4	319.5	914.9	634.4	725.9	177.5	493.6	338.0	338.0
AS	0	0	0	0	0	0	0	0
W 1-3	0	0	0	0	89.2	1017.3	181.1	181.1
W 4	0	0	0	0	93.6	1126.9	166.8	166.8
W 5	396.0	3276.9	727.4	1055.1	396.0	3276.9	727.4	727.4
LA	313.7	3104.3	580.4	890.9	496.0	4930.3	927.5	927.5
Total:	2081.2	13967.4	3921.4	5318.2	2077.1	16764.2	3852.9	3852.9
Cost/add'l mw:		9.98	1.87	2.87		11.15	2.03	2.03
Approx. solution:				5658.7				3854.3

TABLE A-5

Optimal load dispatching and costs for St. Louis power plants
Dispersion Case 3: Light Westerly wind, unstable. Dolomite stack gas cleaning process or low sulfur coal used as required
Problem 1: Net Power Demand of 3000 mw

Costs are per hour

	a) Pollution exposure unit valued at $.10				b) Pollution exposure unit valued at $0			
Plant and Units	Gross Generation, mw	Pollution Exposure Units	Fuel Cost $	Objective Function $	Gross Generation, mw	Pollution Exposure Units	Fuel Cost $	Objective Function $
S 1	250.0	880.6	643.5	731.6	250.0	880.6	643.5	643.5
S 2	424.8	1488.7	1089.9	1238.8	424.8	1489.1	1090.1	1090.1
C 1	0	0	0	0	0	0	0	0
C 5	0	0	0	0	0	0	0	0
V 1	219.1	199.2	650.7	670.7	168.1	151.6	496.5	496.5
V 5	149.1	133.0	439.0	452.3	127.8	113.7	374.5	374.5
M 1	284.0	97.9	737.6	747.4	255.6	85.8	644.9	644.9
M 3	150.0	40.8	349.7	353.8	150.0	40.8	349.7	349.7
M 4	319.5	91.5	767.6	776.8	319.5	91.5	767.6	767.6
AS	0	0	0	0	0	0	0	0
W 1-3	352.3	1645.3	728.5	1191.7	376.8	1732.8	1103.4	1103.4
W 4	93.6	541.0	235.2	289.3	104.0	634.1	267.6	267.6
W 5	396.0	1573.0	1025.6	1182.9	396.0	1573.0	1025.6	1025.6
LA	496.0	4930.0	927.5	1420.5	558.0	5675.0	1111.4	1111.4
Total:	3134.4	11620.1	7893.6	9055.7	3130.6	12468.0	7874.7	7874.7
Cost/add'l mw:		7.45	2.21	3.47		9.28	2.50	2.50
Approx. solution:				9716.0				8460.0

TABLE A-6

Optimal load dispatching and costs for St. Louis power plants
Dispersion Case 3: Light Westerly wind, unstable. Dolomite stack gas cleaning process or low sulfur coal used as required
Problem 2: (a) and (b) -- Net Power Demand of 2000 mw

Costs are per hour

	a) SO_2 pollution exposure unit valued at $.10				b) Pollution exposure unit valued at $.05			
Plant and Units	Gross Generation, mw	Pollution Exposure Units	Fuel Cost $	Objective Function $	Gross Generation, mw	Pollution Exposure Units	Fuel Cost $	Objective Function $
S 1	250.0	880.6	643.5	731.6	155.7	550.0	400.7	428.2
S 2	424.8	1488.7	1090.1	1238.9	371.7	1305.0	948.4	1013.6
C 1	0	0	0	0	0	0	0	0
C 5	0	0	0	0	0	0	0	0
V 1	0	0	0	0	0	0	0	0
V 5	0	0	0	0	0	0	0	0
M 1	255.6	85.8	644.9	653.5	227.2	75.2	565.2	569.0
M 3	150.0	40.8	349.7	353.8	150.0	40.8	349.7	351.7
M 4	319.5	91.5	767.6	776.8	319.5	91.5	767.1	771.7
AS	0	0	0	0	0	0	0	0
W 1-3	0	0	0	0	0	0	0	0
W 4	31.2	177.6	70.9	88.7	41.6	236.6	95.9	95.9
W 5	151.7	595.5	378.9	438.4	316.8	1296.0	801.6	801.6
LA	496.0	4930.0	927.5	1420.5	496.0	4930.0	927.5	927.5
Total:	2078.8	8290.5	4873.1	5702.2	2078.5	8525.1	4856.1	5282.3
Cost/add'l mw:		33.38	1.74	2.86				2.86
Approx. solution:				6087.0				6011.0

TABLE A-7

Optimal load dispatching and costs for St. Louis power plants
Dispersion Case 3: Light Westerly wind, unstable. Dolomite stack gas cleaning process or low sulfur coal used as required
Problem 2: (c) and (d) -- Net Power Demand of 2000 mw

Costs are per hour

Plant and Units	c) SO_2 pollution exposure unit valued at $1.00 and fuel cost not considered				d) SO_2 exposure unit valued at $0			
	Gross Generation, mw	Pollution Exposure Units	Fuel Cost $	Objective Function $	Gross Generation, mw	Pollution Exposure Units	Fuel Cost $	Objective Function $
S 1	168.1	593.4	432.6	593.4	195.3	688.9	502.6	502.6
S 2	424.8	1489.1	1090.1	1489.1	371.7	1305.0	948.4	948.4
C11	0	0	0	0	0	0	0	0
C 5	0	0	0	0	0	0	0	0
V 1	313.0	297.8	999.7	297.8	0	0	0	0
V 5	213.0	197.7	670.3	197.7	0	0	0	0
M 1	284.0	97.9	737.6	97.9	227.2	75.2	565.2	565.2
M 3	150.0	40.8	349.7	40.8	150.0	40.8	349.7	349.7
M 4	355.0	104.7	963.8	104.7	319.5	91.5	767.6	767.6
AS	0	0	0	0	0	0	0	0
W 1-3	0	0	0	0	0	0	0	0
W 4	0	0	0	0	41.6	236.6	95.9	95.9
W 5	198.0	861.6	494.1	861.6	277.2	1157.8	694.3	694.3
LA	0	0	0	0	496.0	4930.0	927.5	927.5
Total:	2105.9	3683.0	5737.9	3683.0	2078.5	8525.9	4851.2	4851.2
Cost/add'l mw:				3.67				2.57
Approx. solution:				5268.0				5196.0

APPENDIX B

B.1 COMPUTER MAPPING ROUTINE "SYMAP"

This model will be concerned with the geographical distribution of air pollution in relation to demographic factors. It will, therefore, be necessary to represent concentration and population data in some consistent numerical form for analytical purposes, and in a graphical form for analysis and interpretation of results. The tool used for both these purposes is the SYMAP computer mapping program, developed first by Professor Howard T. Fisher and expanded and improved at the Laboratory for Computer Graphics and Spatial Analysis. This report uses only one of the three types of maps the program can produce -- contour maps. Like hand-drawn contour maps, they are appropriate for displaying continuously varying values collected at fairly arbitrary "data points". For each map, the coordinate location and data value was given for each sample point, where the sample points represent centers of census tracts or counties, locations of sulfur dioxide measuring stations, or arbitrary grid cells, depending on the map. For the maps in this paper, the number of data points ranged from 40 to 614. From these data, the program uses a two-dimensional interpolation algorithm written by this author to assign an interpolated value to each printed character space on the map. The values are converted to combinations of the standard computer print characters according to a scale specified by the user. On the maps included, supplemental information such as the outline of the study region, the outline of the St. Louis SMSA, and the courses of the Missouri and Mississippi Rivers were also specified (as a sequence of vertices) to improve the readability of the map. The names and locations of the major 1970 power plants are also shown on maps of the Power Plant Study Region. These maps were produced with Versions 5 and 6 of the SYMAP program on the IBM 7094 computer. The population and theoretical air quality maps, originally 23 1/2" x 24", are reproduced at about 31% original size. The larger maps required about 3 minutes each, the smaller map, 1 minute.

B.2 COSTS AND EMISSION RATES UNDER VARIOUS CONTROL PRACTICES

Regulation X by the State of Missouri, and similar regulations by St. Louis county and the City of St. Louis will limit emissions of sulfur dioxide from installations with a capacity in excess of 2 billion BTU/hr to a maximum of 2.3 lbs SO_2 per million BTU input. This will go into effect in October, 1970. I shall assume that the State of Illinois will have similar regulations in effect by late 1970 for Madison, St. Clair and Monroe counties--counties proposed for inclusion in the federally designated St. Louis Air Quality Control Region. Labadie plant, which lies in Franklin County, would not fall under these regulations. In order to comply with these regulations, a unit may (1) burn fuel of lower sulfur content, or (2) remove the sulfur dioxide from stack gases.

An official of the Union Electric Company[29] estimated that coal of no more than 1.4% sulfur content would be needed to comply with this regulation to comply through approach (1). Since there is no practical means of removing sulfur from coal before combustion, naturally low-sulfur coal would need to be purchased. Assuming that coal of 1.4% sulfur could be obtained at an increased cost of $2. per ton, a minimal estimate[29] suggests the use of low sulfur coal would raise fuel costs by 41%.

Removing sulfur oxides from stack gases is a most difficult process, only now emerging into commercial feasibility. The process least expensive and most adaptable to existing plants([8], pp. 8-9) is the limestone/dolomite injection process of Combustion Engineering Co. Using it, the sulfur is washed from the stack gases as sulfites and sulfates of calcium and magnesium[30]. Based on its experience to date with the installation of this process on Meramec unit 2, Union Electric estimates operating costs at $1. per ton of coal, or an increase of 21%. The process is estimated to reduce sulfur dioxide emissions by 90%. The process has a high capital cost of $10. per kwh capacity, which must be considered in deciding whether to install the system, but not in deciding whether to operate it once installed.

Because of the high capital cost, I have assumed that this process would be installed only on the Meramec and Venice installations by the end of 1970, the other units required to control sulfur oxide emissions would use low sulfur coal. For simplicity, fuel and exposure cost functions for case 3 were obtained by multiplying the functions in case 2 by the factors in Table B-1.

The decisions below on fuel switching and control process installation are intended to be representative, although the availability of space for the limestone/dolomite process, or the need for design changes in boilers to accomodate the higher ash fusion temperature of high sulfur coal on individual units were not known. The capital cost for installation of the limestone/dolomite process on the units indicated in Table B-1 (except Meramec 2 where the process is already being installed) would be about $13 million.

TABLE B-1

COST RATIO, EMISSION RATIO, AND PROCESS USED FOR LIMITING SULFUR OXIDE EMISSIONS

Unit	Cost Ratio[a]	Emission Ratio[b]	Control Process
Sioux 1	1.41	0.43	c
Sioux 2	1.41	0.43	c
Cahokia 1-4	1.14	.35	d
Cahokia 5-6	1.41	0.48	c
Venice 1-4	1.21	.10	e
Venice 5-6	1.21	.10	e
Meramec 1-2	1.21	.10	e
Meramec 3	1.21	.10	e
Meramec 4	1.21	.10	e
Ashley	1.00	1.00	f
Wood River 1-3	1.41	.48	c
Wood River 4	1.41	.48	c
Wood River 5	1.41	.48	c
Labadie	1.00	1.00	g

NOTES:

[a] $$\text{cost ratio} = \frac{\text{fuel cost with controls}}{\text{fuel cost without controls}}$$

[b] $$\text{emission ratio} = \frac{\text{uncontrolled } SO_2 \text{ emission rate}}{\text{controlled } SO_2 \text{ emission rate}}$$

[c] Coal with 1.4% sulfur content substituted for present coal.

[d] Desulfurized oil at additional cost of $.40/barrel, and 0.7% sulfur content [29].

[e] Limestone/dolomite injection process. Fuel cost considers operating cost only.

[f] Continued operation on present 1.0% sulfur coal.

[g] Continued operation on high sulfur coal, since plant not located in area subject to emission regulations.

APPENDIX C

COMPUTER GRAPHICS

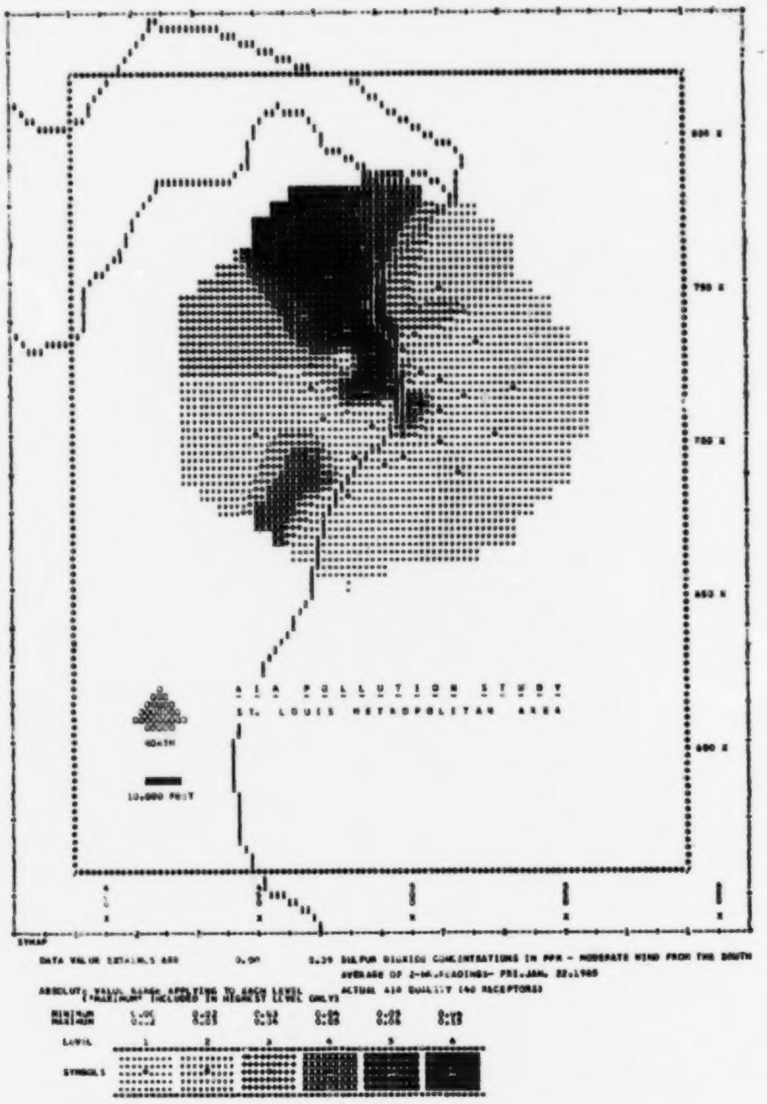
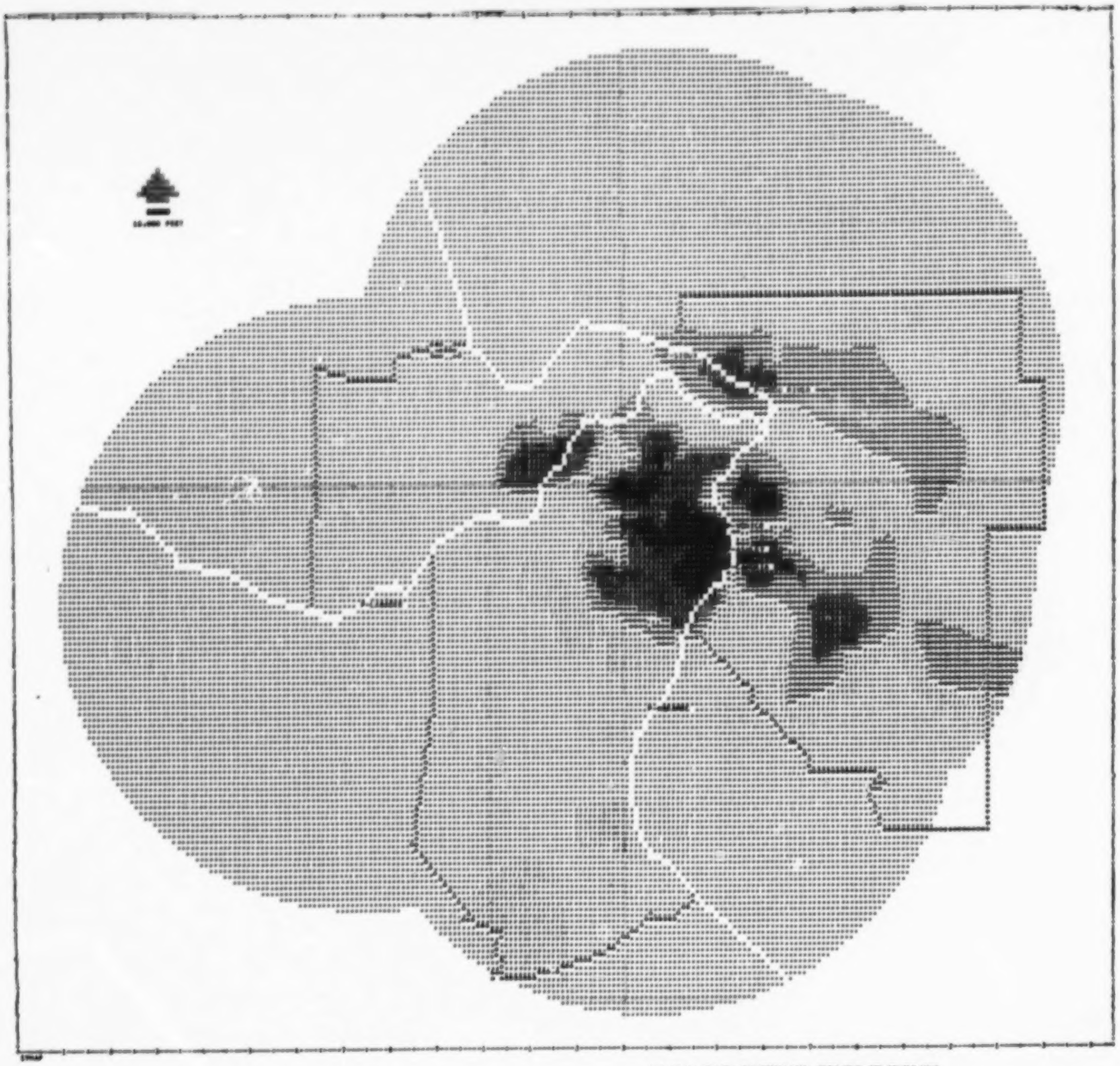

AIR POLLUTION STUDY
ST. LOUIS METROPOLITAN AREA
NORTH
10,000 FEET
800 N
750 N
700 N
650 N
600 N
SYMAP
DATA VALUE EXTREMES ARE 0.00 0.39 SULFUR DIOXIDE CONCENTRATIONS IN PPM - MODERATE WIND FROM THE SOUTH
AVERAGE OF 2-HR.READINGS- FRI.JAN. 22,1965
ACTUAL AIR QUALITY (40 RECEPTORS)
ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
('MAXIMUM' INCLUDED IN HIGHEST LEVEL ONLY)
MINIMUM
MAXIMUM
LEVEL
1
2
3
4
5
6
SYMBOLS

FIGURE C-1

ST. LOUIS REGION STUDY
Power Plant Study Area
Measured SO_2 Concentrations — 22 January 1965



```
POPULATION DENSITY, PROJECTED 1970, POPULATION PER SQUARE MILE
BASED ON 1960 CENSUS TRACTS AND 1970 COUNTY PROJECTIONS BY
THE EAST-WEST GATEWAY COORDINATING COUNCIL, ST LOUIS AREA

SOURCE - U. S. CENSUSES OF POPULATION AND HOUSING, 1960
[illegible]
MISSISSIPPI AND MISSOURI RIVERS INDICATED BY WHITE LINE

ACTUAL DATA VALUE EXTREMES ARE     23.51  [illegible]      ARITHMETIC MEAN IS    [illegible]
                                             STANDARD DEVIATION IS    [illegible]
VALUE LIMITS FOR EACH LEVEL [illegible] HIGHEST LEVEL ONLY)
[illegible]
PERCENTAGE LIMITS FOR EACH LEVEL (BASED ON THE TOTAL VALUE RANGE)
[illegible]

LEVEL        1        2        3        4        5        6

SYMBOLS

NUMBER OF DATA POINTS IN EACH LEVEL   ( TOTAL = [illegible] )
PERCENTAGE OF DATA POINTS IN EACH LEVEL [illegible]
```

FIGURE C-2

ST. LOUIS REGION STUDY
Power Plant Study Area
Projected 1970 Population Density
Mapped by Census Tracts

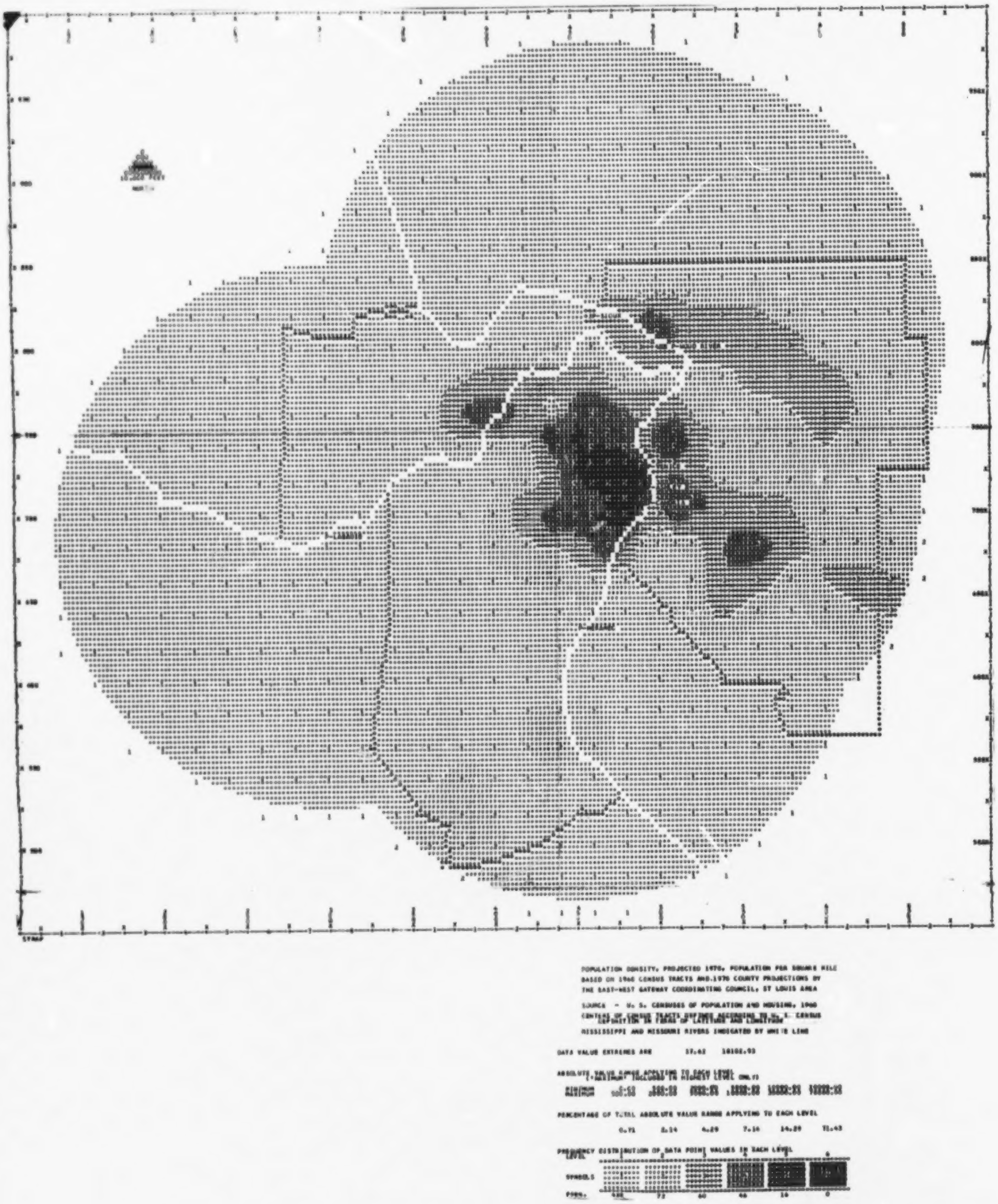

POPULATION DENSITY, PROJECTED 1970, POPULATION PER SQUARE MILE
BASED ON 1960 CENSUS TRACTS AND 1970 COUNTY PROJECTIONS BY
THE EAST-WEST GATEWAY COORDINATING COUNCIL, ST LOUIS AREA
SOURCE - U. S. CENSUSES OF POPULATION AND HOUSING, 1960
CENTERS OF CENSUS TRACTS DEFINED ACCORDING TO U. S. CENSUS
DEFINITION IN TERMS OF LATITUDE AND LONGITUDE
MISSISSIPPI AND MISSOURI RIVERS INDICATED BY WHITE LINE
DATA VALUE EXTREMES ARE 17.62 10102.93
ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MINIMUM
MAXIMUM
PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
0.71 2.14 4.29 7.14 14.29 71.43
FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL
LEVEL 1 2 3 4 5 6
SYMBOLS
FREQ. 72 60 46 16 0
NORTH

FIGURE C-3

ST. LOUIS REGION STUDY
Power Plant Study Area
Projected 1970 Population Density
Mapped by Grid Coordinates

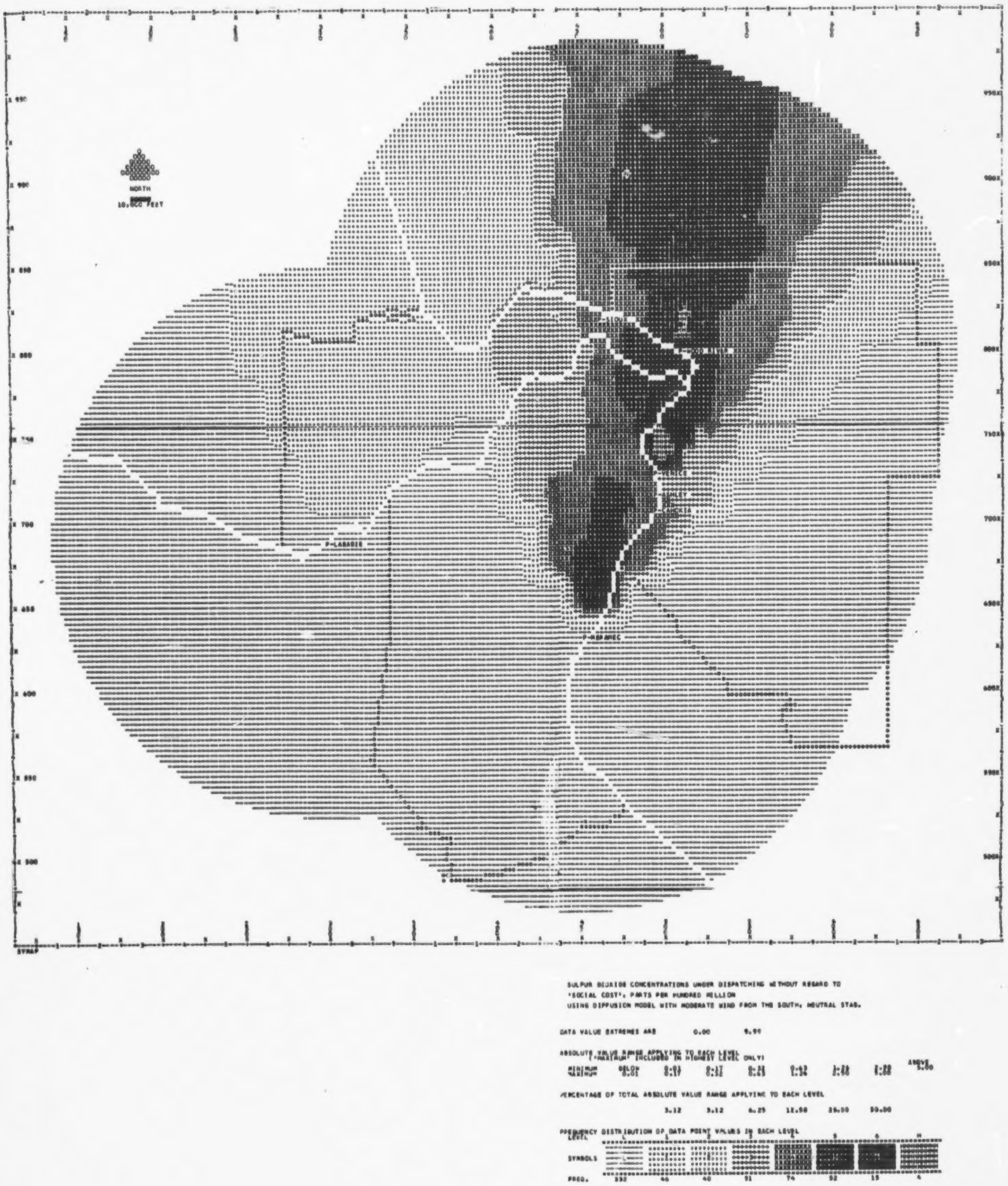

950
900
850
800
750
700
650
600
550
500
NORTH
10,000 FEET
P-SIOUX
P-LABADIE
P-MERAMEC
SYMAP
SULFUR DIOXIDE CONCENTRATIONS UNDER DISPATCHING WITHOUT REGARD TO
'SOCIAL COST', PARTS PER HUNDRED MILLION
USING DIFFUSION MODEL WITH MODERATE WIND FROM THE SOUTH, NEUTRAL STAB.
DATA VALUE EXTREMES ARE 0.00 9.99
ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
('MAXIMUM' INCLUDED IN HIGHEST LEVEL ONLY)
MINIMUM
MAXIMUM
BELOW
ABOVE
PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
3.12 3.12 6.25 12.50 25.00 50.00
FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL
LEVEL L 1 2 3 4 5 6 H
SYMBOLS
FREQ. 332 46 40 51 74 52 13 4

FIGURE C-4

ST. LOUIS REGION STUDY
Power Plant Study Area
Dispatching under Moderate Winds from South
SO_2 Concentrations without Regard to "Social Cost"

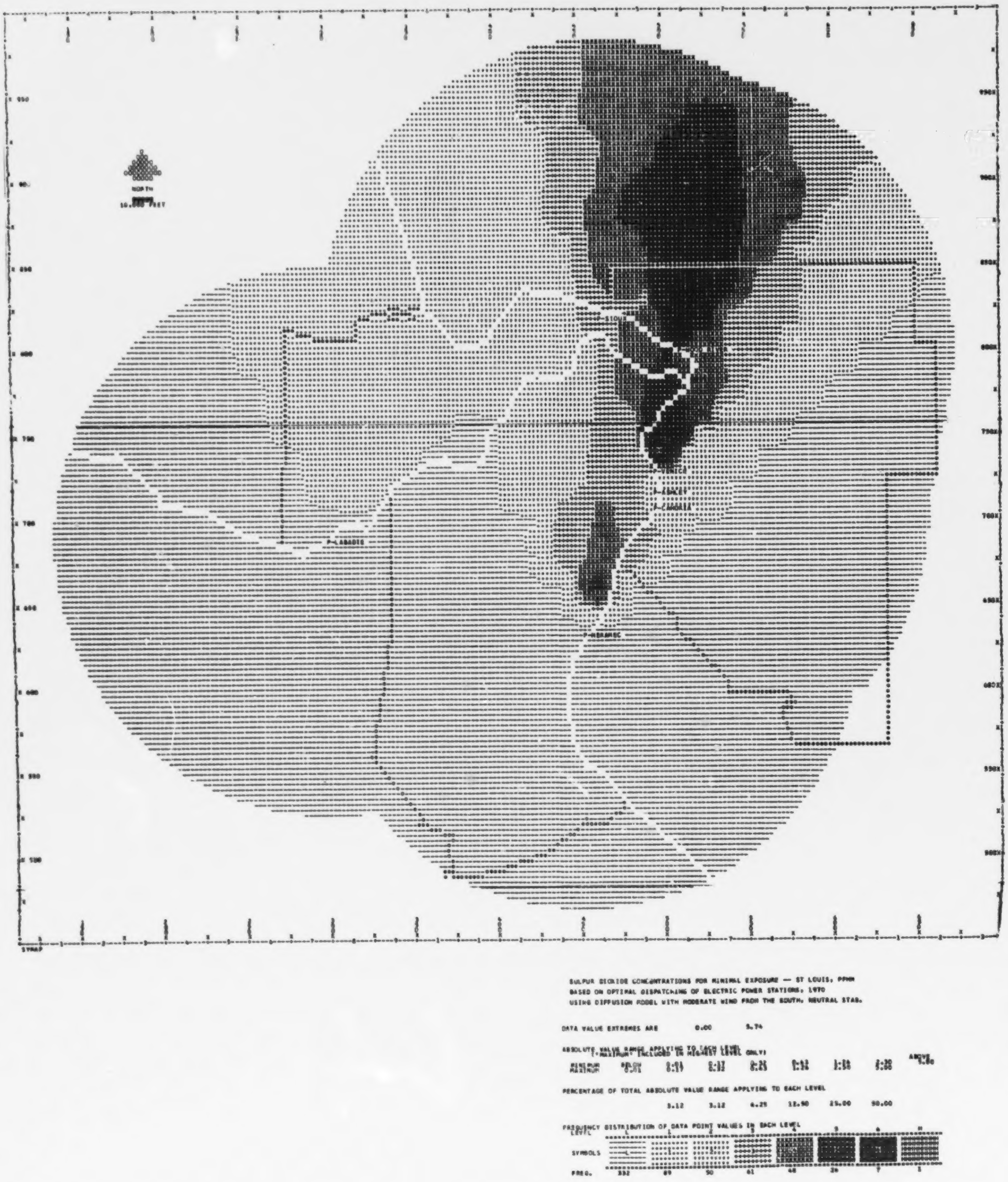
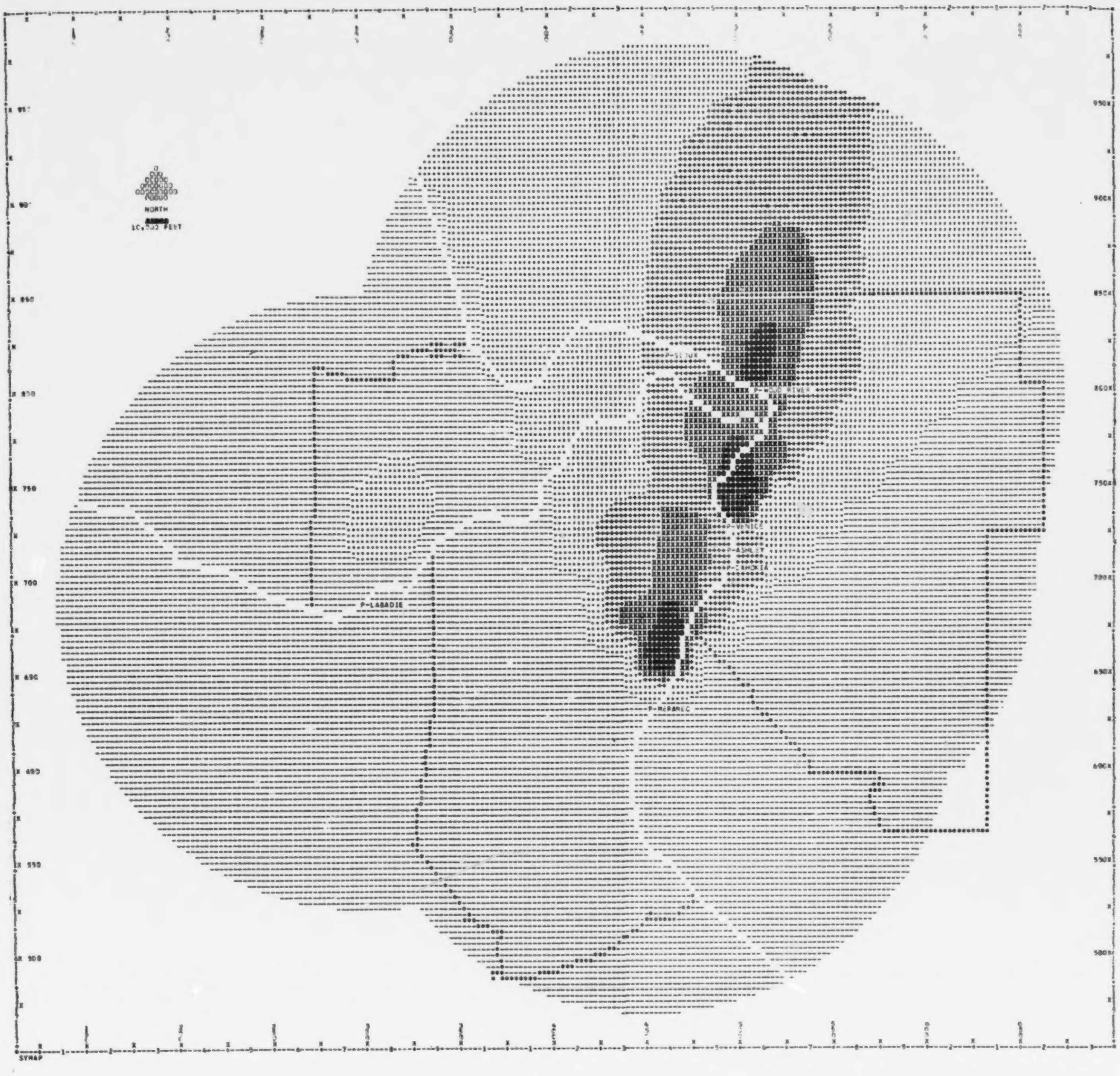

NORTH
10,000 FEET
P-LABADIE
MERAMEC
SULFUR DIOXIDE CONCENTRATIONS FOR MINIMAL EXPOSURE — ST LOUIS, PPHM
BASED ON OPTIMAL DISPATCHING OF ELECTRIC POWER STATIONS, 1970
USING DIFFUSION MODEL WITH MODERATE WIND FROM THE SOUTH, NEUTRAL STAB.
DATA VALUE EXTREMES ARE 0.00 5.74
ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
('MAXIMUM' INCLUDED IN HIGHEST LEVEL ONLY)
MINIMUM
MAXIMUM
BELOW
ABOVE
PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
3.12 3.12 6.25 12.50 25.00 50.00
FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL
LEVEL L 1 2 3 4 5 6 H
SYMBOLS
FREQ. 332 89 50 61 48 26 7 1

FIGURE C-5

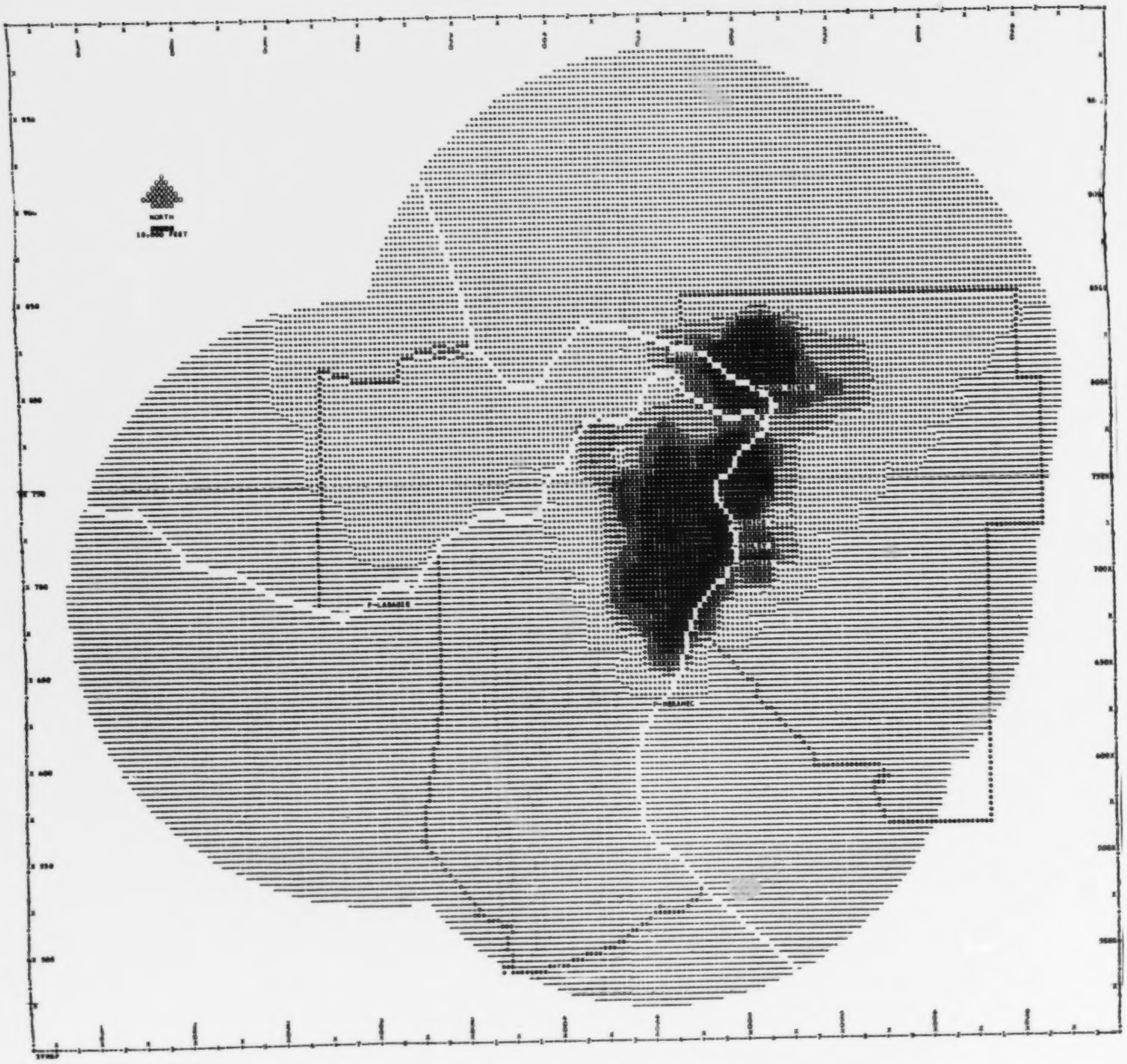
ST. LOUIS REGION STUDY
Power Plant Study Area
Dispatching under Moderate Winds from South
SO_2 Concentrations for Minimal Exposure



```
IMPROVEMENT IN ATM POLLUTION RESULTING FROM 'SOCIAL COST' DISPATCHING
SULFUR DIOXIDE CONCENTRATIONS IN PARTS PER HUNDRED MILLION
USING DIFFUSION MODEL WITH MODERATE WIND FROM THE SOUTH, NEUTRAL STAB.

DATA VALUE EXTREMES ARE        -0.32        4.24

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
      ('MAXIMUM' INCLUDED IN HIGHEST LEVEL ONLY)
  MINIMUM     BELOW     0.01     0.17     0.32     0.63     1.26     2.50
  MAXIMUM      0.01     0.17     0.32     0.63     1.26     2.50     5.00

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
                        3.12     3.12     6.25    12.50    25.00    50.00

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL
  LEVEL          L        1        2        3        4        5        6

  SYMBOLS

  FREQ.        373       47       61       79       40       10        2
```

FIGURE C-6

ST. LOUIS REGION STUDY
Power Plant Study Area
Dispatching under Moderate Winds from South
Improvement in SO_2 through "Social Cost" Dispatching



DENSITY OF EXPOSURE TO POLLUTION UNDER DISPATCHING WITHOUT REGARD TO
"SOCIAL COSTS" — PERSON PARTS PER MILLION PER SQ MI
USING DIFFUSION MODEL WITH MODERATE WIND FROM THE SOUTH, 3000 MW LOAD

DATA VALUE EXTREMES ARE 0.00 541.34

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
('MAXIMUM' INCLUDED IN HIGHEST LEVEL ONLY)

MINIMUM	BELOW	0.01	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	ABOVE
MAXIMUM	0.01	6.26	12.51	25.01	[illegible]	[illegible]	[illegible]	[illegible]

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

3.12 3.12 6.25 12.50 25.00 50.00

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	L	1	2	3	4	5	6	H
SYMBOLS	☰	⠿	⠿	▤	▦	■	■	■
FREQ.	232	107	12	19	21	33	22	8

FIGURE C-7

ST. LOUIS REGION STUDY
Power Plant Study Area
Dispatching under Moderate Winds from South
Density of Exposure to Pollution without Regard to "Social Cost"

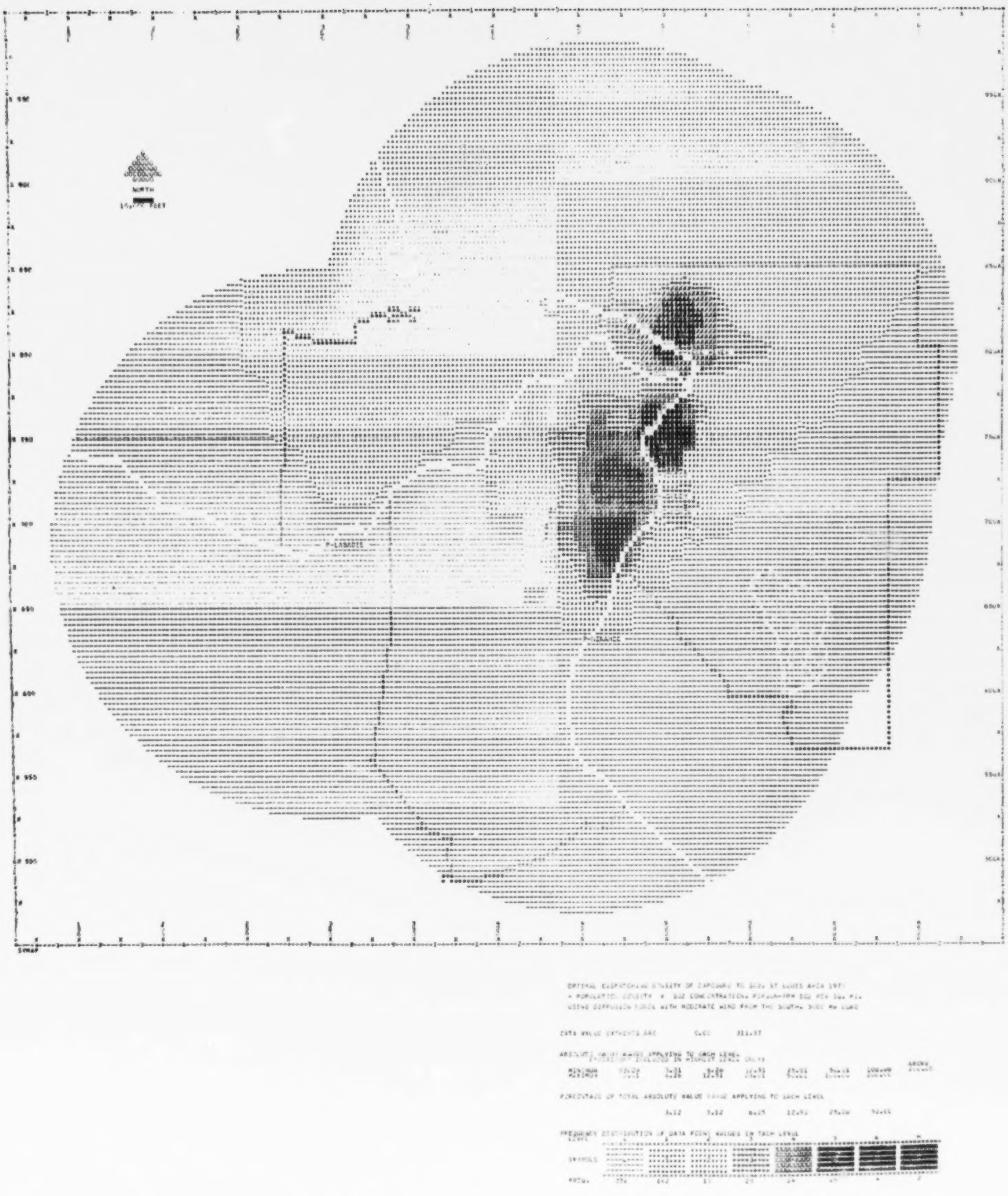

NORTH
P-LABADIE
SYMAP

FIGURE C-8

ST. LOUIS REGION STUDY
Power Plant Study Area
Dispatching under Moderate Winds from South

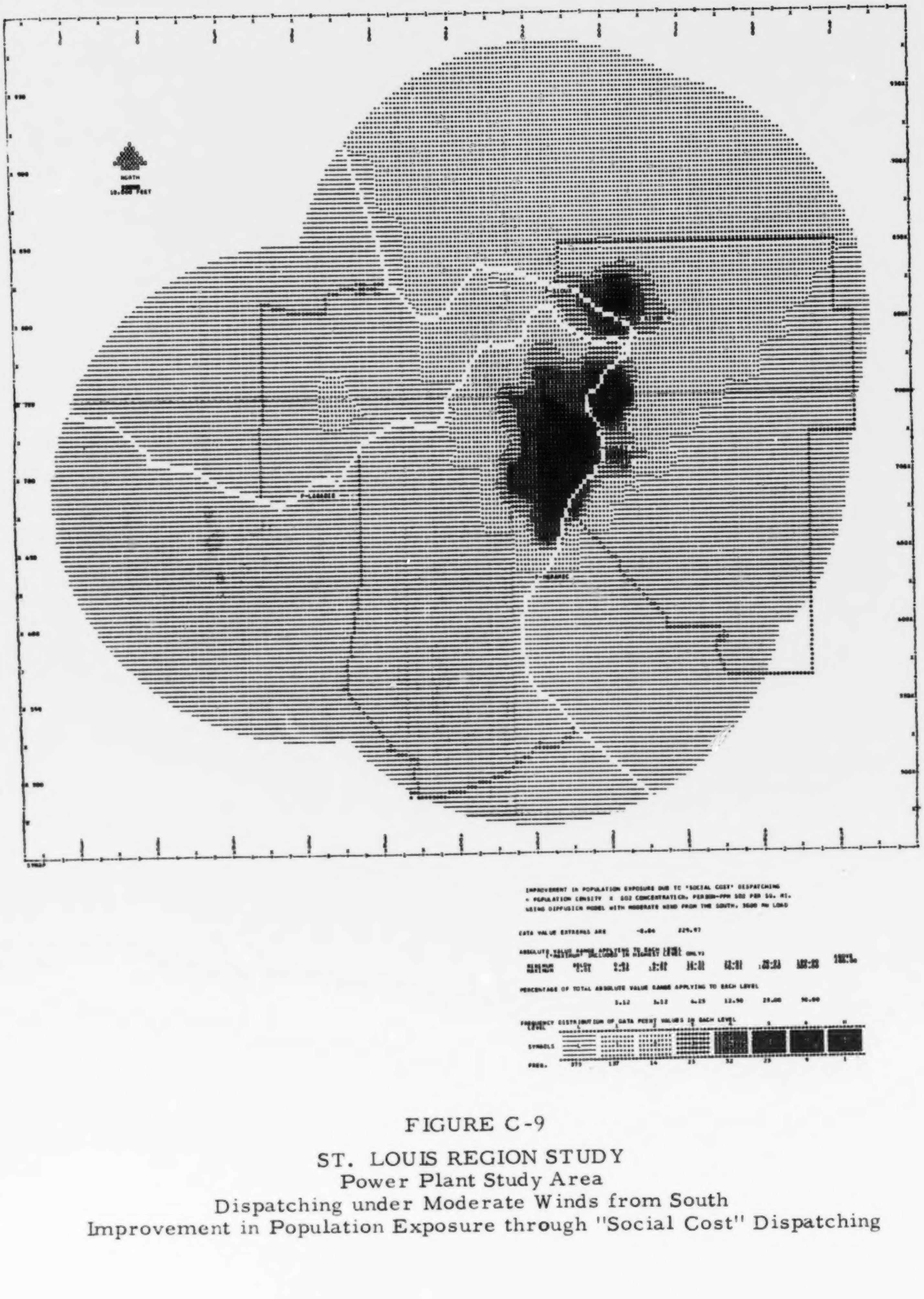

NORTH
10,000 FEET
P-SIOUX
P-LABADIE
P-MERAMEC
IMPROVEMENT IN POPULATION EXPOSURE DUE TO "SOCIAL COST" DISPATCHING
= POPULATION DENSITY X SO2 CONCENTRATION, PERSON-PPM SO2 PER SQ. MI.
USING DIFFUSION MODEL WITH MODERATE WIND FROM THE SOUTH, 3600 MW LOAD
DATA VALUE EXTREMES ARE -0.04 229.97
ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
3.12 3.12 6.25 12.50 25.00 50.00
FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL
LEVEL
SYMBOLS
FREQ.
375 137 14 21 32 23 9 1

FIGURE C-9

ST. LOUIS REGION STUDY
Power Plant Study Area
Dispatching under Moderate Winds from South
Improvement in Population Exposure through "Social Cost" Dispatching

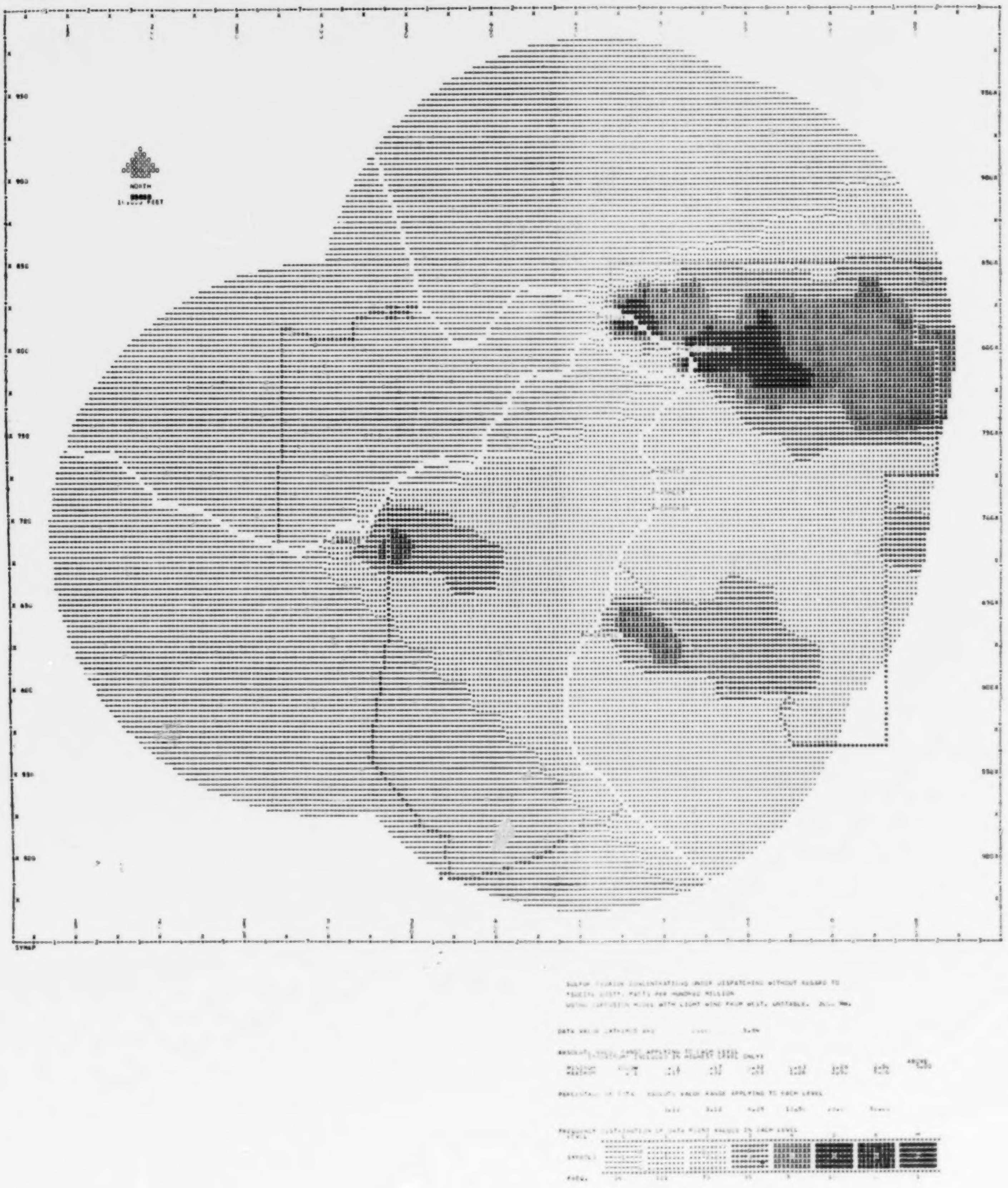
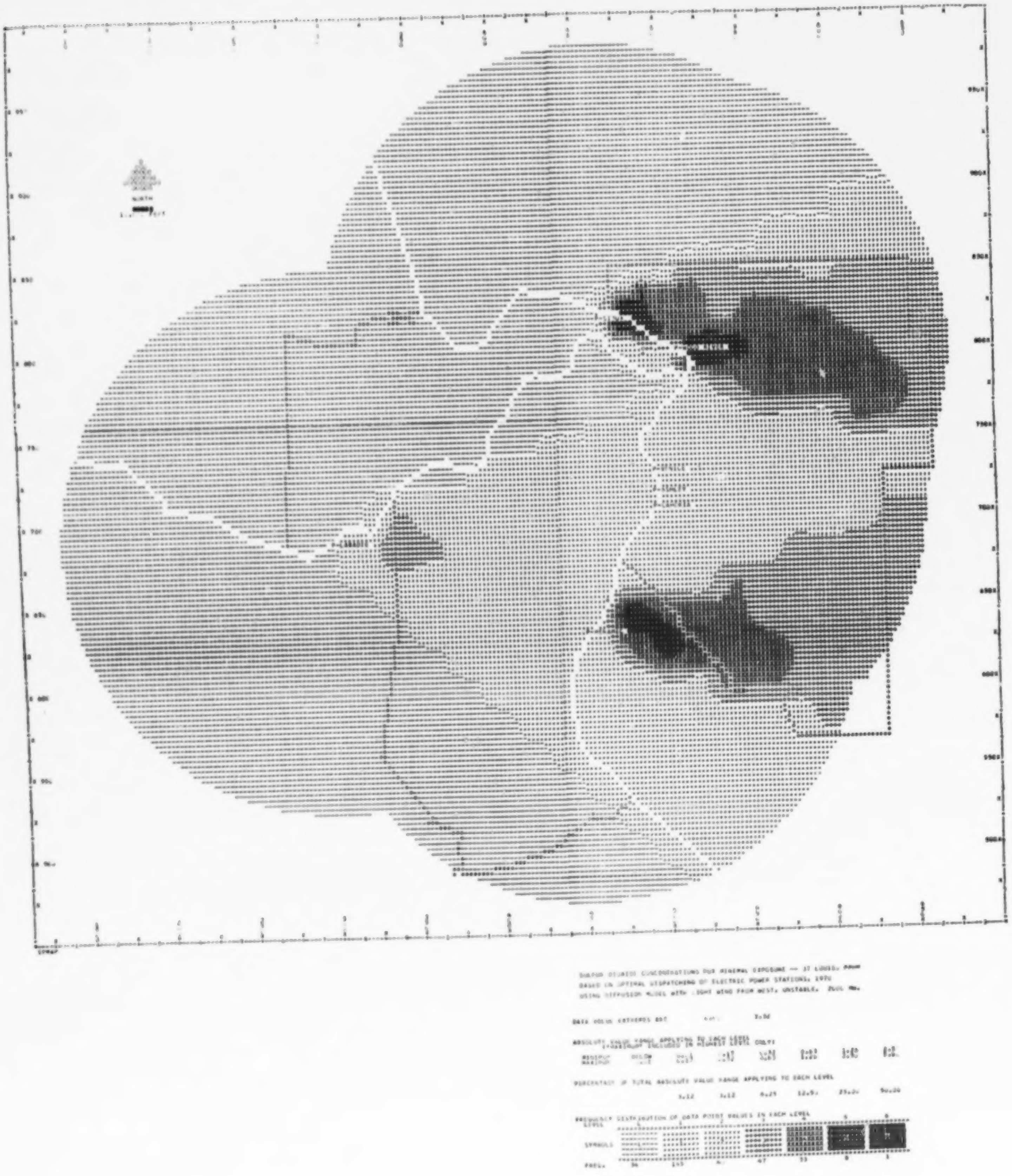


FIGURE C-10

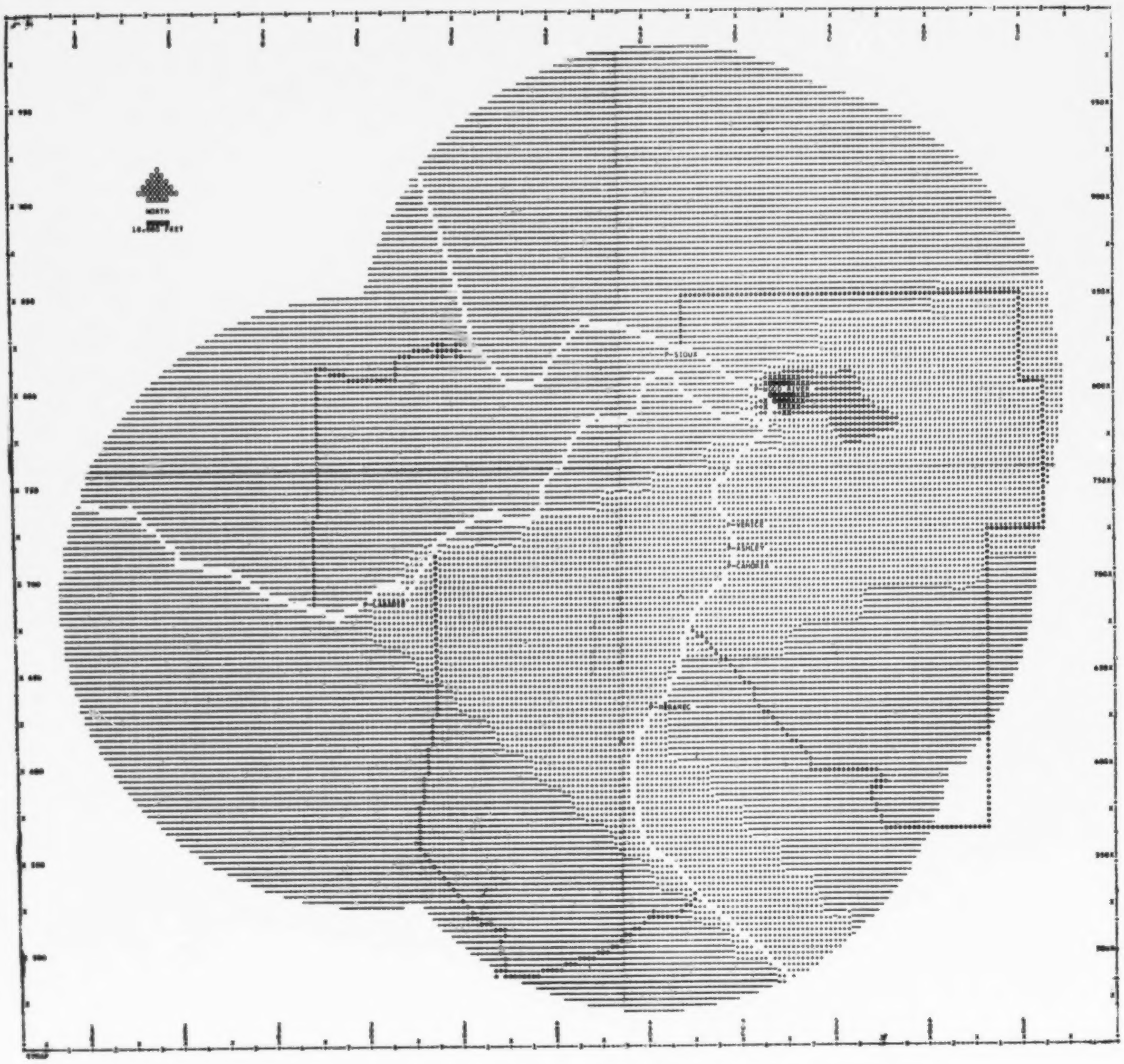
ST. LOUIS REGION STUDY
Power Plant Study Area
Dispatching under Light Winds from West
SO_2 Concentrations without Regard to "Social Cost"



NORTH
USING DIFFUSION MODEL WITH LIGHT WIND FROM WEST, UNSTABLE.
ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL
LEVEL
SYMBOLS
FREQ.

FIGURE C-11

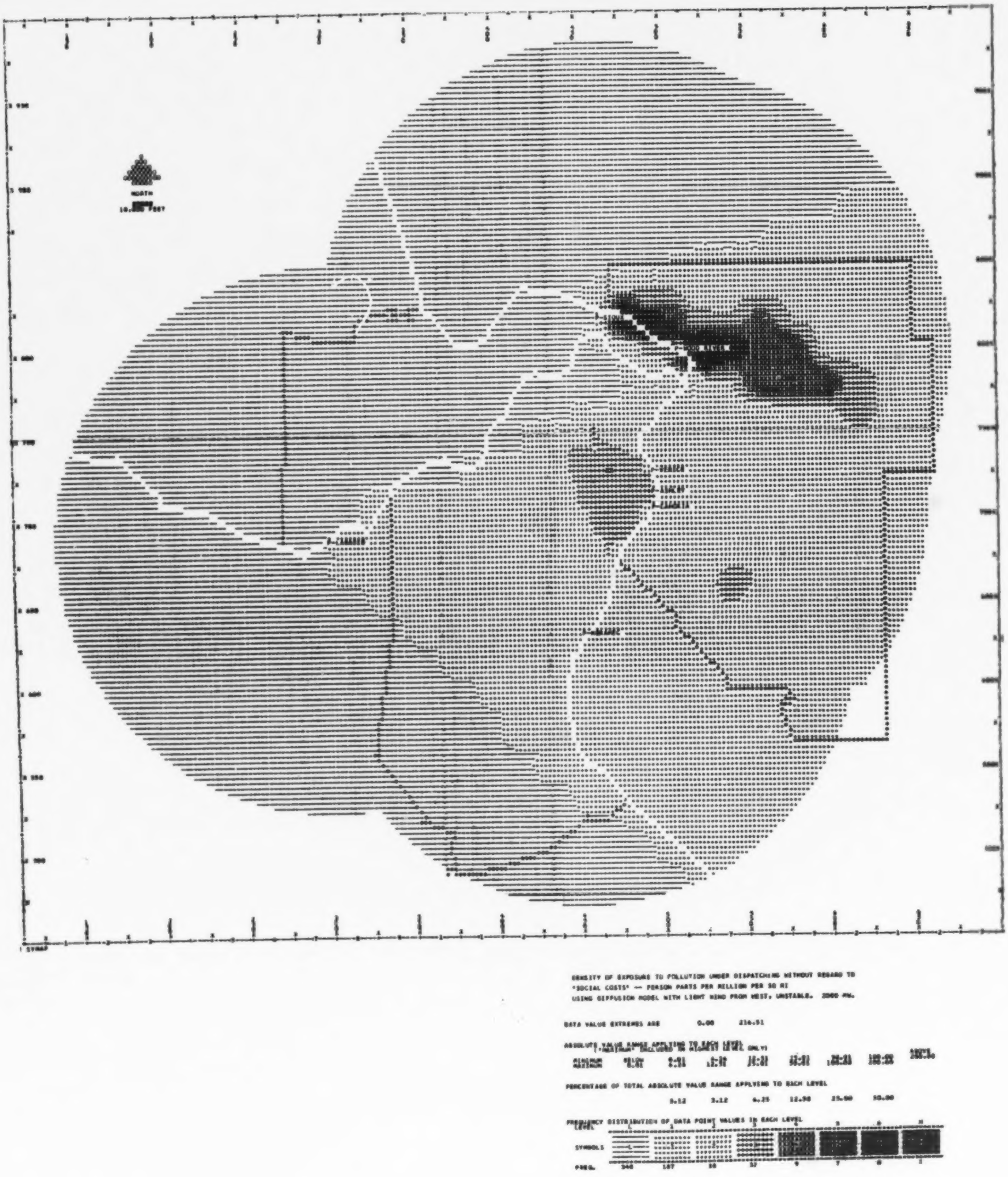
ST. LOUIS REGION STUDY
Power Plant Study Area
Dispatching under Light Winds from West
SO_2 Concentrations without Regard to "Social Cost"



```
IMPROVEMENT IN AIR POLLUTION RESULTING FROM 'SOCIAL COST' DISPATCHING
SULFUR DIOXIDE CONCENTRATIONS IN PARTS PER HUNDRED MILLION
USING DIFFUSION MODEL WITH LIGHT WIND FROM WEST, UNSTABLE.  2000 MW.

DATA VALUE EXTREMES ARE        -6.99        2.92

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
    ('MAXIMUM' INCLUDED IN HIGHEST LEVEL ONLY)
 MINIMUM     BELOW    [illegible]  [illegible]  [illegible]  [illegible]  [illegible]  [illegible]
 MAXIMUM      0.01    [illegible]  [illegible]  [illegible]  [illegible]  [illegible]  [illegible]

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

                         3.12     3.12     6.25    12.50    25.00    50.00

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL
 LEVEL         L        1        2        3        4        5        6
 SYMBOLS
 FREQ.        425      107       17        4        0        0        1
```

FIGURE C-12

ST. LOUIS REGION STUDY
Power Plant Study Area
Dispatching under Light Winds from West
Improvement in SO_2 through "Social Cost" Dispatching



DENSITY OF EXPOSURE TO POLLUTION UNDER DISPATCHING WITHOUT REGARD TO
"SOCIAL COSTS" — PERSON PARTS PER MILLION PER SQ MI
USING DIFFUSION MODEL WITH LIGHT WIND FROM WEST, UNSTABLE. 2000 HR.

DATA VALUE EXTREMES ARE 0.00 216.51

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
('MAXIMUM' INCLUDED IN HIGHEST LEVEL ONLY)

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

3.12 3.12 6.25 12.50 25.00 50.00

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	L	1	2	3	4	5	6	H
FREQ.	346	187	30	37	9	7	8	3

FIGURE C-13

ST. LOUIS REGION STUDY
Power Plant Study Area
Dispatching under Light Winds from West
Density of Exposure to Pollution without Regard tc "Social Cost"

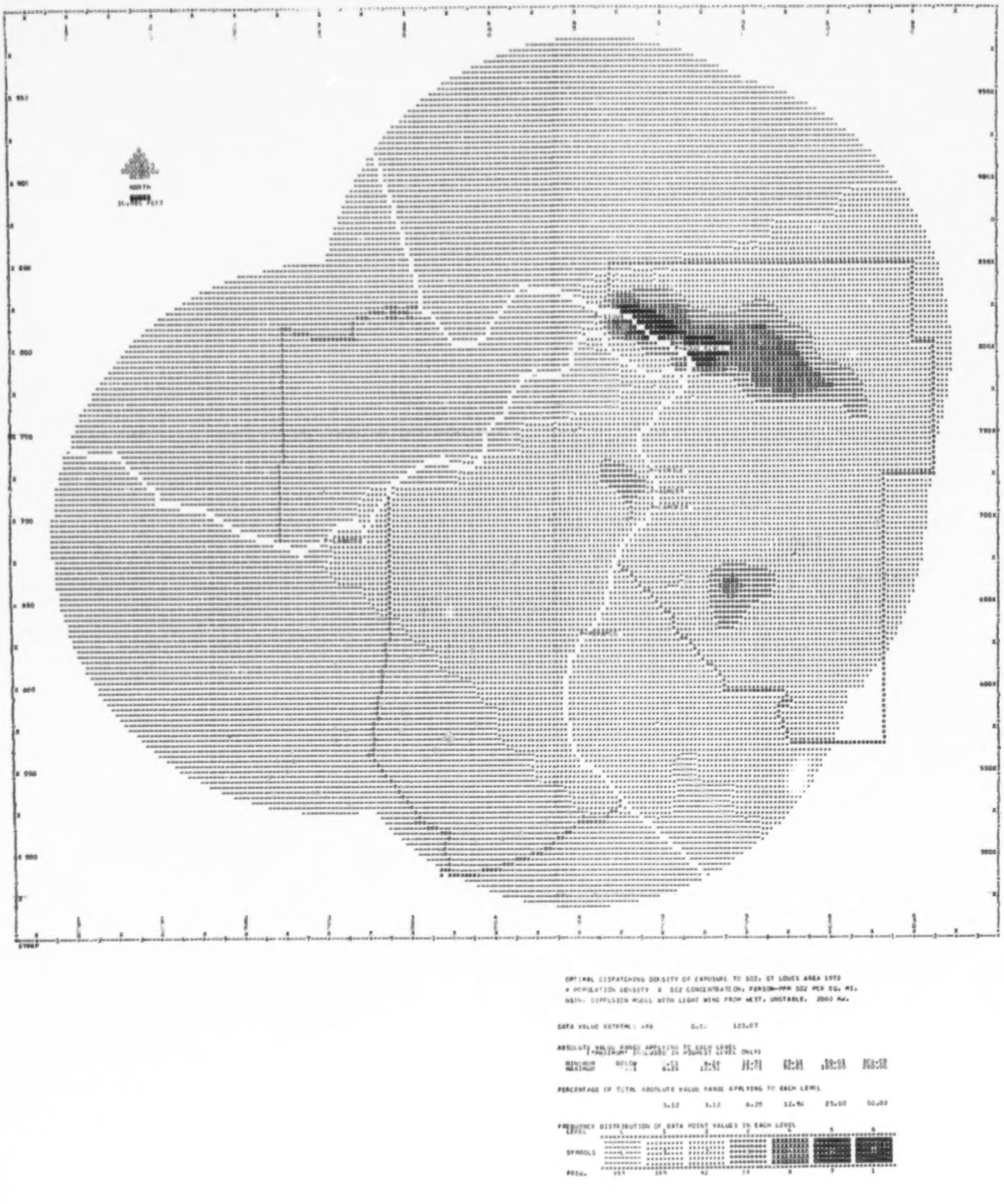
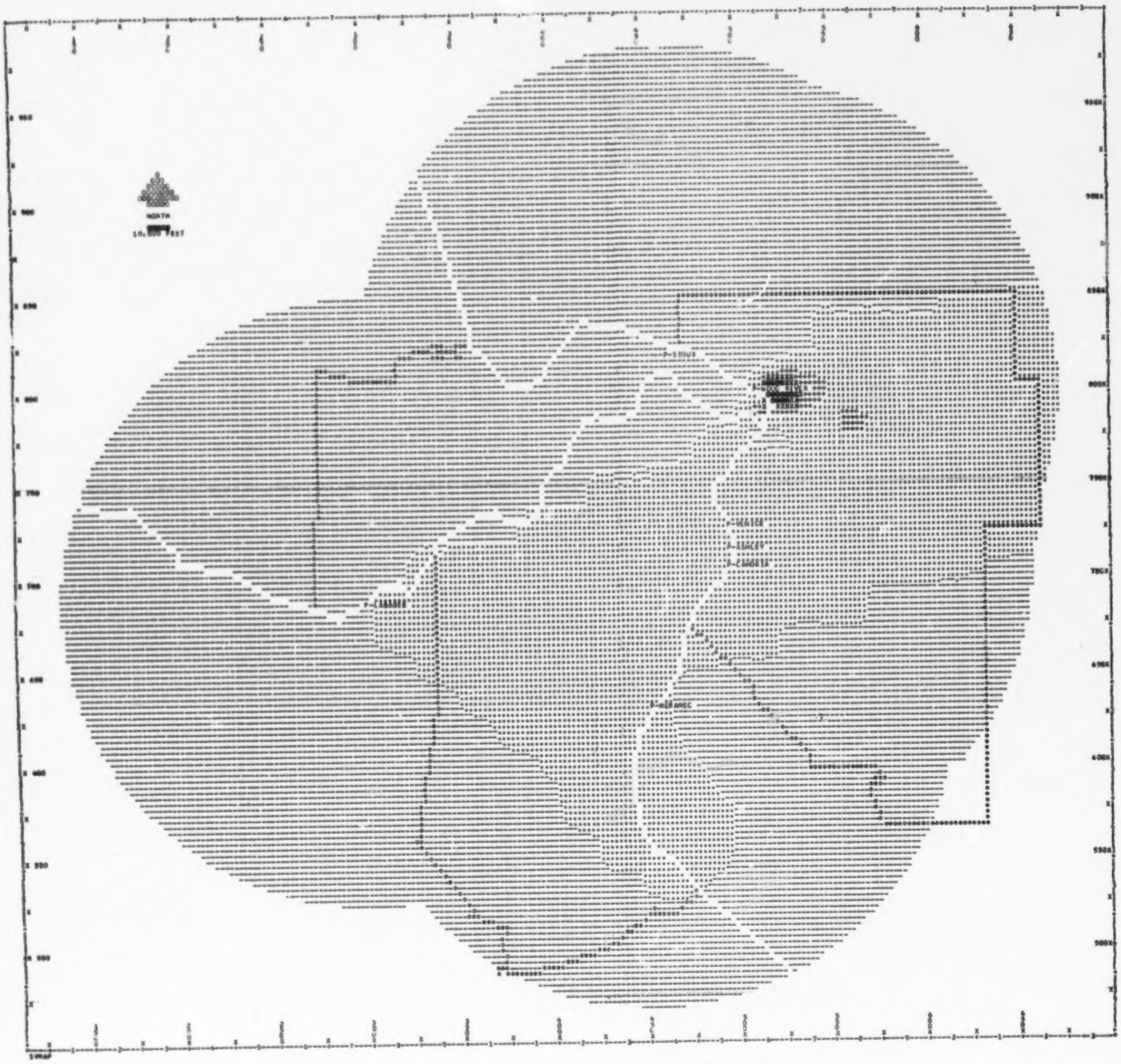

NORTH
OPTIMAL DISPATCHING DENSITY OF EXPOSURE TO SO2, ST LOUIS AREA 1970
= POPULATION DENSITY X SO2 CONCENTRATION, PERSON-PPM SO2 PER SQ. MI.
USING DIFFUSION MODEL WITH LIGHT WIND FROM WEST, UNSTABLE. 2000 MW.
DATA VALUE EXTREMES ARE 0.0 123.07
ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
('MAXIMUM' INCLUDED IN HIGHEST LEVEL ONLY)
MINIMUM
MAXIMUM
PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
3.12 3.12 6.25 12.50 25.00 50.00
FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL
LEVEL
SYMBOLS
FREQ.

FIGURE C-14

ST. LOUIS REGION STUDY
Power Plant Study Area
Dispatching under Light Winds from West
Optimal Dispatching Density of Exposure



```
IMPROVEMENT IN POPULATION EXPOSURE DUE TO 'SOCIAL COST' DISPATCHING
= POPULATION DENSITY  X  SO2 CONCENTRATION, PERSON-PPM SO2 PER SQ. MI.
USING DIFFUSION MODEL WITH LIGHT WIND FROM WEST, UNSTABLE.  2000 MW.

DATA VALUE EXTREMES ARE        -12.74       93.44

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
      ('MAXIMUM' INCLUDED IN HIGHEST LEVEL ONLY)

MINIMUM     BELOW      [illegible]  [illegible]  [illegible]  [illegible]  [illegible]  [illegible]
MAXIMUM     [illegible] [illegible] [illegible]  [illegible]  [illegible]  [illegible]  [illegible]

PERCENTAGE OF TOT   .SOLUTE VALUE RANGE APPLYING TO EACH LEVEL

                    3.12      3.12      6.25      12.90     25.00     50.00

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL
LEVEL         1         2         3         4         5         6

SYMBOLS

FREQ    441      155        15         2         0         1         0
```

FIGURE C-15

ST. LOUIS REGION STUDY
Power Plant Study Area
Dispatching under Light Winds from West
Improvement in Population Exposure through "Social Cost" Dispatching